Atmospheric and Oceanic Science Letters 16 (2023) 100352

Contents lists available at ScienceDirect

Atmospheric and Oceanic Science Letters

journal homepage: http://www.keaipublishing.com/en/journals/atmospheric-and-oceanic-science-letters/

Perspective

Will the summer sea ice in the Arctic reach a tipping point?

Ola M. Johannessen[a,*], Elena V. Shalina[b]

[a] Nansen Scientific Society, Bergen, Norway
[b] Nansen International Environmental and Remote Sensing Centre, St. Petersburg, Russia

ARTICLE INFO

Keywords:
Sea ice
Arctic
Climate change
Tipping point

ABSTRACT

The Arctic sea-ice cover has decreased in extent, area, and thickness over the last six decades. Most global climate models project that the summer sea-ice extent (SIE) will decline to less than 1 million (mill.) km^2 in this century, ranging from 2030 to the end of the century, indicating large uncertainty. However, some models, using the same emission scenarios as required by the Paris Agreement to keep the global temperature below 2°C, indicate that the SIE could be about 2 mill. km^2 in 2100 but with a large uncertainty of ±1.5 mill. km^2. Here, the authors take another approach by exploring the direct relationship between the SIE and atmospheric CO_2 concentration for the summer–fall months. The authors correlate the SIE and $\ln(CO_2/CO_2r)$ during the period 1979–2022, where CO_2r is the reference value in 1979. Using these transient regression equations with an R^2 between 0.78 and 0.87, the authors calculate the value that the CO_2 concentration needs to reach for zero SIE. The results are that, for July, the CO_2 concentration needs to reach 691 ± 16.5 ppm, for August 604 ± 16.5 ppm, for September 563 ± 17.5 ppm, and for October 620 ± 21 ppm. These values of CO_2 for an ice-free Arctic are much higher than the targets of the Paris Agreement, which are 450 ppm in 2060 and 425 ppm in 2100, under the IPCC SSP1-2.6 scenario. If these targets can be reached or even almost reached, the "no tipping point" hypothesis for the summer SIE may be valid.

1. Introduction

The Arctic is very sensitive to global warming, where changes in the surface air temperature (SAT) are usually at least the double those of the Northern Hemisphere because of Arctic Amplification (e.g., Johannessen et al., 2016; Fang et al., 2022). This has impacted the melting of the Arctic sea-ice cover over the last six decades (e.g., Johannessen and Shalina, 2022; Fig. 1).

During the period 1979–2022, a 44-year period where we have reliable satellite microwave sensor data, the mean September (summer minimum) sea-ice extent (SIE) has decreased dramatically, by 39.7%, while in March (winter maximum) it has decreased by 11.8% and annually by 18.2%. The September sea-ice area (SIA), which is less than the SIE, has decreased by 45.8%, in March by 10.7%, and annually by 18.8% (Nansen Environmental and Remote Sensing Center (NERSC) Arctic Sea Ice Observing System; https://iceobs.nersc.no). This also implies that at least 45.8% of the multiyear ice that was present at the beginning of the cold season has been lost, because the definition of multi-year ice is the ice which has survived the summer melt. However, SIA estimates are less accurate than SIE estimates owing to melt ponds on the surface of the ice cover being wrongly interpreted as ocean in the satellite microwave data (Kern et al., 2016), indicating that the SIA is slightly larger. The sea-ice thickness at the end of the melt season has also decreased dramatically, by 2 m, from the submarine detection period 1958–2000 to the CryoSat altimeter period in 2011–2018, causing a loss in volume of 5130 km^3/10 yr in the fall (Kwok, 2018).

The summer minimum SIE in mid-September for 2021 and 2022 was 5.54 and 5.40 mill. km^2, respectively, which is about 1.3 mill. km^2 larger than the minimum record in 2012 of 4.17 mill. km^2. (It should also be mentioned that using the same satellite data, the National Snow and Ice Data Center (https://nsidc.org/data/seaice_index) calculated an SIE minimum for mid-September 2022 of 4.87 mill. km^2, which is 0.53 mill. km^2 less than the NERSC calculation. This is caused by the different retrieval algorithms used, e.g., Ivanova et al. (2014); however, the trends are the same for these two datasets.) But was this increase caused only by interannual variability or was the summer ice in the stage of stabilization through some recovery mechanism (e.g., Tietsche et al., 2011)?

In a recent assessment of the ice cover, Meier and Stroeve (2022) wrote that "the future of Arctic sea ice is dependent on future CO_2 emissions, but a seasonally ice-free Arctic Ocean is likely in the coming decades". However, in contrast, Johannessen and Shalina (2022) hypothesized that there will be "no tipping point" for the summer ice minimum if the Paris Agreement target can be reached, which requires a CO_2 concentration in the atmosphere of 450 ppm in

* Corresponding author.
E-mail address: ola.johannessen@nansenscientificsociety.no (O.M. Johannessen).

https://doi.org/10.1016/j.aosl.2023.100352
Received 16 January 2023; Revised 6 February 2023; Accepted 1 March 2023
Available online 4 March 2023

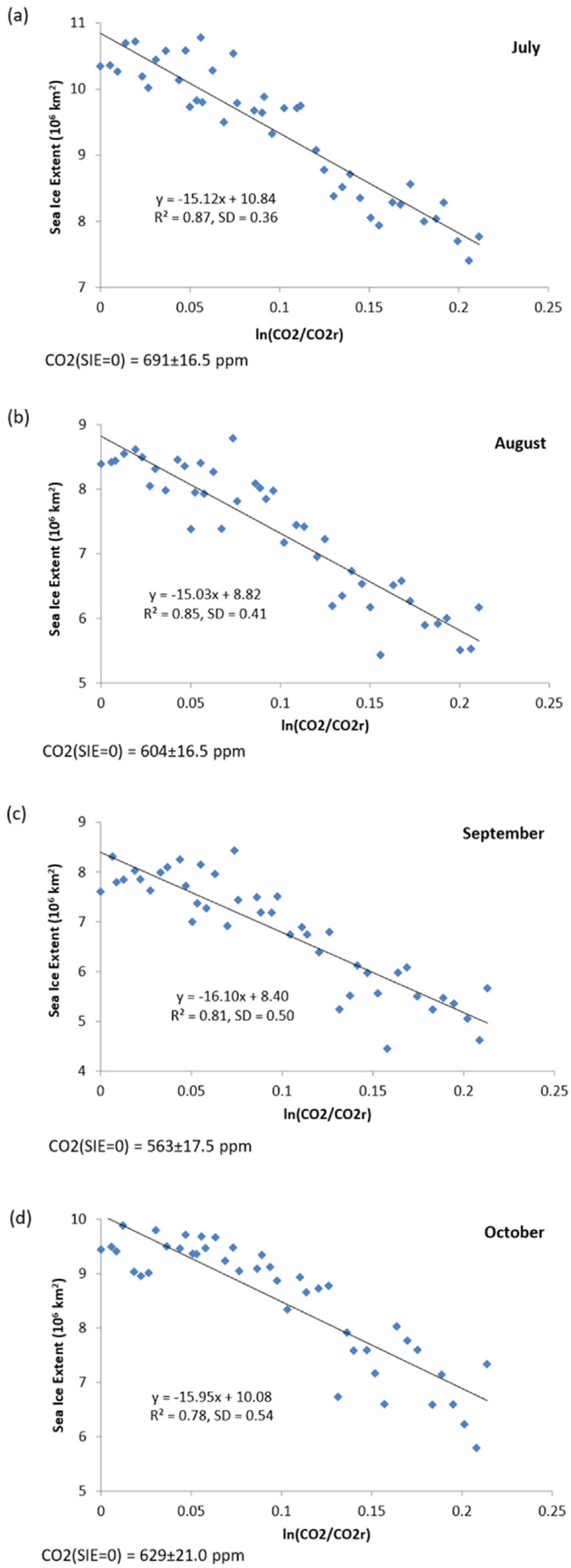

Fig. 1. Empirical relationship between the monthly CO_2 concentration ($\ln(CO_2/CO_2r)$) and Arctic SIE in (a) July, (b) August, (c) September, and (d) October. The panels show the regression equation, coefficient of determination (R^2), standard error (standard deviation (SD) of the estimate), and the estimated CO_2 concentrations for SIE=0 and their uncertainty in ppm.

2060, and 425 ppm in 2100, using the Shared Socioeconomic Pathways (SSP)1-2.6 scenario (Table SPM.1 in IPCC, 2021), compared to a mean of 415 ppm in October 2022.

The Arctic sea-ice cover has been considered one of the first and foremost examples of a climate tipping element (Lenton et al., 2008), although now the question of whether or not the sea-ice cover indeed has a tipping point is controversial. The concept of "tipping points" is a unifying metaphor that refers not only to a critical threshold where a nonlinear and potentially abrupt and irreversible change occurs (Lenton, 2012), but can also refer to a transformation to a fundamentally new state, with the potential to lead to cascading impacts—a so-called "impact" tipping point (Armstrong McKay et al., 2022). Here, we use the term "tipping point" to refer to an essentially ice-free Arctic in summer, representing a new state, with cascading impacts on the ocean climate, marine ecosystems, fisheries, and the economy in the Arctic (Johannessen et al., 2020), as well as potential impacts on the Polar Jet stream and in the mid and lower latitudes through teleconnections—e.g., the East Asian summer monsoon in China (Guo et al., 2014) and the Indian summer monsoon extreme precipitation (Chatterjee et al., 2021).

In this perspective, we review the expected decline of Arctic sea ice in the summer–fall period in the coming decades, based on both numerical modeling and the empirical relationship between the SIE and the CO_2 concentration in the atmosphere, including new results. We present evidence that supports the contention that the summer sea-ice cover will not necessarily reach a tipping point.

2. Numerical modeling projections of SIE in response to CO_2

There have been many papers reporting projections of the summer ice minimum, so here we only mention a few. Nearly two decades ago, Johannessen et al. (2004) used two then state-of-the–art GCMs, the ECHAM4 model from the Max Planck Institute for Meteorology, Germany, and HadCMF3 from the Hadley Centre for Climate Prediction and Research, UK, to project the SIE for summer and winter up to the period 2081–90. The scenario for forcing used was IPCC IS92, which is similar to the IPCC Special Report on Emissions Scenarios (SRES) B2, reaching a CO_2 concentration in the atmosphere of about 600 ppm in the year 2090, which is slightly higher than the 570 ppm doubling of CO_2 since the industrial revolution. The projections for SIE for the winter (March) up to the period 2081–90 indicated for both models a reduction of 20% from the period 2001–10, and for the summer (September) a reduction of about 80% (Fig. 9 in Johannessen et al., 2004), comparable to the projection for September summer ice by Gregory et al. (2002). It should be mentioned that these summer SIE projections are very conservative, with a CO_2 concentration of 600 ppm in 2090, when compared to the Paris Agreement as mentioned above.

Holland et al. (2006), Winton (2006), and Eisenman and Wettlaufer (2009) each performed modeling studies to evaluate the potential for future abrupt sea-ice loss and critical threshold behavior. Winton (2006) investigated whether the Arctic sea ice has a tipping point in the sense of an inherent instability. Different modeling runs forced with SRES A1B and A2 gave different results, i.e., some models projected an abrupt decrease in higher emission scenarios after a warming threshold was reached, whereas in other modeling runs the transition to ice-free conditions was more linear, with no evident tipping point dynamics. Holland et al. (2006) considered whether tipping point dynamics could lead to abrupt reductions in the summer sea ice, using 16 models forced by IPCC SRES A1B. Abrupt reductions in the 21st century occurred in simulations from over 50% of the models, and it was suggested that reductions in future greenhouse gas emissions moderate the likelihood of these events. However, there is large spread and uncertainties among different models. The Eisenman and Wettlaufer (2009) modeling study of physical processes found that critical threshold behavior is unlikely during the transition from current perennial sea-ice conditions toward a seasonally ice-free Arctic Ocean.

Stroeve et al. (2007) concluded that 13 IPCC AR4 GCMs forced by the IPCC SRES A1B scenario reaching a CO_2 concentration in the atmosphere of 720 ppm in 2100, projected that the September SIE will be less than 1 mill. km^2 in 2050, reduced from 8.3 mill. km^2 in 1900. An SIE of less than 1 mill. km^2 is commonly arbitrarily used as an ice-free or nearly ice-free Arctic Ocean.

Wang and Overland (2009) selected 6 of 23 CMIP3 GCMs based on observational constraint to project the September SIE up to 2100 forced by the IPCC SRES A1B and A2 scenarios reaching CO_2 concentrations of 720 ppm and 850 ppm in 2100. The mean projected timeframe for a nearly ice-free Arctic Ocean in September was 2037, while a later study by Overland and Wang (2013) indicated a nearly ice-free Arctic Ocean in 2040 based on reviewing several CMIP5 GCMs forced by the Representative Concentration Pathway (RCP) 8.5 scenario reaching 960 ppm in 2100, 10 years earlier than in Stroeve et al. (2007). However, it should be mentioned that the scenarios used in these studies were very high—varying between the SSP4-6.0 and the SSP5-8.5 scenarios (O'Neill et al., 2017; Gidden et al., 2019) for these GCMs simulations, which is probably not realistic.

Meleshko et al. (2020) studied the September SIE decrease with 33 CMIP5 GCMs in the period 1900–2100 using the forcing scenarios RCP4.5 and RCP8.5 reaching a CO_2 concentration in the atmosphere in 2100 of 450 ppm for RCP4.5, similar to the SSP1-2.6 scenario (target for the Paris Agreement), and the very high concentration of 960 ppm for RCP8.5, about 60 ppm less than SSP5-8.5. The result using RCP4.5 (SSP1-2.6) was that the SIE at the end of the century was still 2.5 mill. km^2, while with the RCP8.5 scenario the SIE was below 1 mill. km^2 in 2075.

Recent studies by SIMIP (2020) and Davy and Ouetten (2020) using CMIP6 models with SSP scenarios gave more-or-less the same result, projecting that the Arctic Ocean potentially could be nearly ice free (less than 1 mill. km^2) before 2050 and onwards, depending on the scenario. However, their result using SSP1-2.6 projected that the SIE would be about 2 mill. km^2 in 2100 with an uncertainty of $\pm$1.5 mill. km^2 (Davy and Ouetten, 2020). Shen et al. (2021) compared 36 CMIP6 models with 24 CMIP5 models during the period 1979–2014 and concluded that the CMIP6 models had a smaller spread than the CMIP5 models and that the internal variability for the CMIP6 models contributed approximately 22% $\pm$ 5% to the decline in September SIE. Docquier and Koenigk (2021) analyzed 33 CMIP6 GCMs with respect to Arctic SIA, in which they selected the best models that captured the observed decline of SIA and the northward ocean heat transport under the high SSP5-8.5 and low SSP1-2.6 scenarios. For the high scenario, they projected a nearly ice-free Arctic Ocean in 2035, and for the low scenario at the end of this century.

However, all the CMIP6 model simulations, including previous GCM simulations, show a large spread and therefore the projection of the Arctic sea ice in this century remains uncertain. It is generally accepted that GCMs still need major improvements in order to give more reliable projections for Arctic sea ice and an assessment of whether a tipping point threshold exists.

3. Empirical relationship between SIE and CO_2

The main driver of global warming is the emission of greenhouse gases, among which CO_2 is the most important. Therefore, using the direct relationship between the SIE and the CO_2 concentration in the atmosphere during the past several decades is an alternative approach to projecting the level of CO_2 values required for the SIE to disappear during summer in the future.

The first paper to explore this direct relationship between the SIE and the CO_2 concentration in the atmosphere was published by Johannessen (2008), in which it was shown using annual values that 90% of the SIE decline could be explained by the increasing CO_2 concentration during the period 1961–2007. It was also shown that the correlation between the annual mean zonal SAT from 70°N to the North Pole and the SIE was $R^2 = 0.64$, indicating that about 60% of the SIE decline could be caused by the SAT alone. This was interpreted as the SAT being the major physical driver of the declining SIE through the high correlation between the CO_2 and SAT of 0.76. However, the magnitude of the correlation between the SIE and CO_2 was even higher (−0.95), indicating that this correlation with the CO_2 integrated other processes, such as natural variability, in addition to the SAT.

The next paper to deal with this relationship for the summer minimum month (September) was also by Johannessen (2011), but here the SIE was correlated for a longer period (1901–2010) with the $\ln(CO_2/CO_2r)$ since this is the empirical law for longwave radiation back to space from the surface of the earth (Myhr et al., 1998). The CO_2r was the reference level of CO_2 at the start of the time series in 1901 of 296 ppm. Here, it was shown that 84% of the mean September ice decline could be explained by the increase in CO_2 concentration in the atmosphere. By solving the regression equation for SIE equal to zero, the CO_2 must reach 502 ppm for a total melt, which is much higher than in the Paris Agreement, indicating no "tipping point" for the summer ice.

Another paper that dealt with this topic correlated a linear relationship between the monthly mean September SIA and cumulative CO_2 emissions, indicating that the summer ice will be lost under an approximate addition of 1000 Gt of CO_2 emissions to the atmosphere (Notz and Stroeve, 2016). Here, it was claimed that the September ice will be less than 1 mill. km^2 before 2050. However, the authors commented that if a rapid reduction in CO_2 emissions could be achieved, fulfilling the target of a global temperature of 1.5°C, the summer ice will have a chance to survive. We do, however, have some critical points to make regarding this paper, because they correlated the SIA with cumulative CO_2 emissions to the atmosphere rather than the concentration of CO_2 in the atmosphere, which is the physical cause of the reduction in SIA. Furthermore, they directly used CO_2 and not $\ln(CO_2/CO_2r)$. In this context, it should also be mentioned that about 50% of CO_2 emissions to the atmosphere are absorbed by the ocean and land (IPCC, 2021), which is another reason to use the CO_2 concentration in the atmosphere instead of the total emissions, since this uptake by land and ocean could have varied during their observation period and may also change in the future. In a more recent paper, Stroeve and Notz (2018) again correlated the SIE with the cumulative total emissions of CO_2, now indicating that the Arctic Ocean could be ice-free in August and September if the cumulative emissions reach 800 $\pm$ 300 Gt of CO_2, and in July to October if the cumulative emissions of CO_2 reach 1400 $\pm$ 300 Gt of CO_2, again with large error bars.

Recently, we updated the Johannessen (2011) result by again correlating the SIE with the $\ln(CO_2/CO_2r)$, for the summer–fall months, July–October, in the period 1979–2021, a 43-year period using satellite data from www.icobs.nersc.no and CO_2 data from www.gml.noaa.gov/cogg/trends/. The CO_2r in 1979 for July was 337 ppm, for August was 335 ppm, for September was 333 ppm, and for October was 334 ppm. As seen from Fig. 1, the SIE will decline to zero if the CO_2 reaches 691 $\pm$ 16.5 ppm for July, 604 $\pm$ 16.5 ppm for August, 563 $\pm$ 17.5 ppm for September, and 620 $\pm$ 21 ppm for October. The coefficient of determination (R^2) values are 0.87, 0.84, 0.81, and 0.78 for July, August, September, and October, respectively, thus explaining 78% to 87% of the declining SIE by the increasing CO_2. The remaining SIE not explained by the CO_2 increase is natural variability primarily caused by the variability of SAT, Arctic Amplification, Arctic Oscillation, North Atlantic Oscillation, Pacific Decadal Oscillation, Atlantic Multidecadal Variability, the Transpolar Current causing variation in sea-ice export through Fram Strait, and ice-edge ocean eddies transporting ice out to the warm waters causing melting of the ice edge—all reviewed in Johannessen et al. (2020). However, it should be mentioned that these results are based on monthly average values and the minimum in the middle of September is about 0.15 mill. km^2 less than the mean, which means that zero ice for the minimum in September requires that the CO_2 should be about 10 ppm less than for the mean CO_2. All these values of CO_2 for zero SIE for the summer–fall period are well above the

Paris Agreement of 450 ppm in 2060 and 425 ppm in 2100, supporting our hypothesis that there will be no tipping point for the summer ice, even if the Paris Agreement cannot totally be reached.

4. Summary and conclusion

The September SIE has declined by 39.7% since 1979, with a record minimum in 2012. However, in 2021 and 2022, the September minimum was about 1.3 mill. km^2 higher than in 2012. Therefore, has the summer ice started to stabilize or is it only interannual variability?

We have reviewed the future of the summer ice, focusing on the September minimum, by commenting on two approaches—one by reviewing GCM results for the SIE, and the other in which we explore the direct relationship between the SIE and the CO_2 in the atmosphere.

GCMs show a large scatter for all selected scenarios, and it is only the SSP1-2.6 scenario, which is the same as what is necessary to reach the Paris Agreement target, that indicates that the September SIE will survive, albeit reduced to about 2 mill. km^2. However, even for this scenario, the scatter is large, at ±1.5 mill. km^2 (Davy and Ouetten, 2020). The conclusion is that GCMs still require major improvements to project the ice cover in the Arctic. However, even if GCMs are improved, the modeling community will still have problems with which realistic scenario they should use for the longer-term projections to the end of this century.

Our approach has been to explore the direct relationship between the SIE and the $\ln(CO_2/CO_2r)$ during the period 1979–2021, where CO_2r is the reference level in 1979. We are using these regression equations for the summer–fall months, July to October, and asking the question as to what level the CO_2 must reach in order that the SIE should be zero—that is, no summer ice cover in the Arctic Ocean. This is of course an extrapolation based on the transient relationship above, where we have had a significant increase in CO_2 in the atmosphere and a strong decline in the ice cover. Therefore, it is a conservative extrapolation for the development of summer ice in the future. Our extrapolation indicates that July could be ice-free if the CO_2 concentration in the atmosphere potentially reaches 691 ppm, while for August the CO_2 required would be 604 ppm, for September it would be 563 ppm, and for October it would be 629 ppm. (However, in our study, we have used the monthly mean values, while the minimum in September is 0.15 mill. km^2 less than the mean. For a minimum September SIE, the values for the CO_2 will be approximately 10 ppm lower that the value of the mean for zero SIE, which is of no significance for our conclusions). These values for a potentially ice-free Arctic Ocean for the summer–fall months are far above the Paris Agreement of 450 ppm for 2060 and 425 ppm for 2100. Even if these targets cannot be fully reached, the CO_2 emissions will be reduced, causing a much lower CO_2 concentration in the atmosphere than our conservative estimate of the CO_2 concentration for a summer–fall ice-free Arctic Ocean. Therefore, this supports our hypothesis for there being no inevitable tipping point for the summer ice in the Arctic Ocean. Again, this is another example of how important a reduction in CO_2 emissions to the atmosphere is in the coming years, including an exponential increase of renewable energy and limiting per capita emissions (particularly from the population in the industrial part of the world). Furthermore, we should also attempt to limit the world's population growth, which is causing the increase in emissions impacting the climate (e.g., Johannessen and Shalina, 2022) and is projected to be 9.7 billion in 2060 (Vollset et al., 2020).

Data availability

All data in the main text are freely available.

Funding

The authors acknowledge funding support from the Nansen Scientific Society.

Declaration of Competing Interests

The authors declare no competing interests.

Acknowledgments

The authors thank Martin Miles of the NORCE Norwegian Research Centre for his suggestions and editing.

References

Armstrong McKay, D.I., Staal, A., Abrams, J.F., Winkelmann, R., Sakschewski, B., Loriani, S., Fetzer, I., Cornell, S.E., Rockström, J., Lenton, T.M., 2022. Exceeding 1.5°C global warming could trigger multiple climate tipping points. Science 377, eabn7950. doi:10.1126/science.abn7950.

Chatterjee, S., Ravichandran, M., Murukesh, N., Raj, R.P., Johannessen, O.M., 2021. A possible relation between Arctic sea ice and late season Indian summer monsoon rainfall extremes. Clim. Atmos. Sci. 4, 36. doi:10.1038/s41612-021-00191-w.

Davy, R., Outten, S., 2020. The Arctic surface climate in CMIP6: Status and developments since CMIP5. J. Clim. 33, 8047–8068. doi:10.1175/JCLI-D-19-0990.1.

Docquier, D., Koenigk, T., 2021. Observation-based selection of climate models projects Arctic ice-free summers around 2035. Commun. Earth Environ. 2, 144. doi:10.1038/s43247-021-00214-7.

Eisenman, I., Wettlaufer, J.S., 2009. Nonlinear threshold behavior during the loss of Arctic sea ice. Proc. Nat. Acad. Sci. 106, 28–32. doi:10.1073/pnas.0806887106.

Fang, M., Li, X., Chen, H.W., Chen, D., 2022. Arctic amplification modulated by Atlantic multidecadal oscillation and greenhouse forcing on multidecadal to century scales. Nature Commun. 13, 1865. doi:10.1038/s41467-022-29523-x.

Gidden, M.J., Riahi, K., Smith, S.J., Fujimori, S., Luderer, G., Kriegler, E., van Vuuren, D.P., et al., 2019. Global emissions pathways under different socioeconomic scenarios for use in CMIP6: a dataset of harmonized emissions trajectories through the end of the century. Geosci. Model Dev. 12, 1443–1475. doi:10.5194/gmd-12-1443-2019.

Gregory, J.M., Stott, P.A., Cresswell, D.J., Rayner, N.A., Gordon, C., Sexton, D.M.H., 2002. Recent and future changes in Arctic sea ice simulated by the HadCM3 AOGCM. Geophys. Res. Lett. 29, 2175. doi:10.1029/2001GL014575.

Guo, D., Gao, Y., Bethke, I., Gong, D., Johannessen, O.M., Wang, H., 2014. Mechanism on how the spring Arctic sea ice impacts the East Asian summer monsoon. Theor. Appl. Climatol. 115, 107–119. doi:10.1007/s00704-013-0872-6.

Holland, M.M., Bitz, C.M., Tremblay, B., 2006. Future abrupt reductions in the summer Arctic sea ice. Geophys. Res. Lett. 33, L23503. doi:10.1029/2006GL028024.

IPCC (Intergovernmental Panel on Climate Change), 2021. Climate Change 2021: The physical science basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. (Masson-Delmotte, V. et al. (Eds.)). Cambridge University Press, Cambridge, United Kingdom and New York, USA, 2391 pp. doi:10.1017/9781009157896.

Ivanova, N., Johannessen, O.M., Pedersen, L.T., Tonboe, R.S., 2014. Retrieval of Arctic sea ice parameters by satellite passive microwave sensors: A comparison of eleven sea ice concentration algorithms. IEEE Trans. Geosci. Remote Sens. 52, 7233–7246. doi:10.1109/TGRS.2014.231013.

Johannessen, O.M., 2008. Decreasing Arctic sea ice mirrors increasing CO_2 on decadal time scale. Atmos. Ocean. Sci. Lett. 1, 51–56. doi:10.1080/16742834.2008.11446766.

Johannessen, O.M., 2011. Arctic climate – Present and future perspectives. In: Given at the Symposium to Honour the Scientific Works of Klaus Hasselmann on his 80 years birthday, 9–10 November 2011. Hamburg, Germany.

Johannessen, O.M., Bengtsson, L., Miles, M.W., Kuzmina, S.I., Semenov, V.A., Alekseev, G.V., Nagurnyi, A.P., et al., 2004. Arctic climate change: Observed and modelled temperature and sea ice variability. Tellus A 56, 328–341. doi:10.3402/tellusa.v56i4.14418.

Johannessen, O.M., Bobylev, L., Shalina, E.V., Sandven, S., 2020. Sea Ice in the Arctic. Springer Polar Sciences. Springer, p. 525. doi:10.1007/978-3-030-21301-5.

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

Johannessen, O.M., Shalina, E.V., 2022. Population increase impacts the climate, using the sensitive Arctic as an example. Atmos. Ocean. Sci. Lett. 15, 100192. doi:10.1016/j.aosl.2022.100192.

Kern, S., Rødsal, A., Pedersen, L.T., Ivanova, N., Saldo, R., Tomboe, R.T., 2016. The impact of melt ponds on summertime microwave brightness temperature and sea ice concentrations. Cryosphere 10, 2217–2239. doi:10.5194/to-10-2217-2016.

Kwok, R., 2018. Arctic sea ice thickness, volume, and multiyear ice coverage: Losses and coupled variability (1958–2018). Environ. Res. Lett. 13, 105005. doi:10.1088/1748-9326/aae3ec.

Lenton, T.M., 2012. Arctic climate tipping points. Ambio 41, 10–22. doi:10.1007/sl3280-011-0221-x.

Lenton, T.M., Held, H., Kriegler, E., Hall, J., Lucht, W., Rahmstorf, S., Schellnhuber, H.J., 2008. Tipping elements in the Earth's climate system. Proc. Nat. Acad. Sci 105, 1786–1793. doi:10.1073/pnas.0705414105.

Meier, W.N., Stroeve, J., 2022. An updated assessment of the changing Arctic sea ice cover. Oceanography doi:10.5670/oceanog.2022.114.

Meleshko, V.P., Pavlova, T., Bobylev, L.P., Golubkin, P., 2020. Current and projected sea ice in the Arctic in the twenty-first century. In: Johannessen, O.M., Bobylev, L.P., Shalina, E.V., Sandven, S. (Eds.), Sea Ice in the Arctic. Springer Polar Sciences, Springer. doi:10.1007/978-3-030-21301-5.

Myhr, G., Highwood, E.J., Shine, K., Stordal, F., 1998. New estimates of radiative forcing due to well mixed greenhouse gasses. Geophys. Res. Lett. 14, 2715–2718. doi:10.1029/98GL01908.

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

O'Neill, B.C., Kriegler, E., Ebi, K.L., Kemp-Benedict, E., Riahi, K., Rothman, D.S., van Ruijven, B.J., et al., 2017. The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. Global Environ. Change 42, 169–180. doi:10.1016/j.gloenvcha.2015.01.004.

Overland, J.E., Wang, M., 2013. When will the summer Arctic be nearly sea ice free? Geophys. Res. Lett. 40, 2097–2101. doi:10.1002/gel.50316.

Shen, Z., Duan, A., Li, D., Li, J., 2021. Assessment of ranking of climate models in Arctic ice cover simulations from CMIP5 to CMIP6. J. Clim. 34, 3609–3627. doi:10.1175/JCLI-D-20-0294.1.

SIMIP Community, 2020. Arctic sea ice in CMIP6. Geophys. Res. Lett. 47, e2019GL086749. doi:10.1029/2019GL086749.

Stroeve, J., Holland, M.M., Meier, W., Scambos, T., Serreze, M., 2007. Arctic sea ice decline: faster than forecast. Geophys. Res. Lett. 34, L09501. doi:10.1029/2007GL029703.

Stroeve, J., Notz, D., 2018. Changing state of Arctic sea ice across all seasons. Environ. Res. Lett. 13, 103001. doi:10.1088/1748-9326/aade56.

Tietsche, S., Notz, D., Jungclaus, J.H., Marotzke, J., 2011. Recovery mechanisms of Arctic summer sea ice. Geophys. Res. Lett. 38, L02707. doi:10.1029/2010GL045698.

Vollset, S.E., Goren, E., Yuan, C.-W., Cao, J., Smith, A.E., Hsiao, T., Bisignano, C., et al., 2020. Fertility, mortality, migration, and population scenarios for 195 countries and territories from 2017 to 2100: A forecasting analysis for the Global Burden of Disease Study. Lancet 396, 1285–1306. doi:10.1016/S0140-6736(20)30677-2.

Wang, M., Overland, J.E., 2009. A sea ice free summer Arctic within 30 years. Geophys. Res. Lett. 36, L07502. doi:10.1029/2009GL037820.

Winton, M., 2006. Does the Arctic sea ice have a tipping point? Geophys. Res. Lett. 33, L23504. doi:10.1029/2006GL028017.