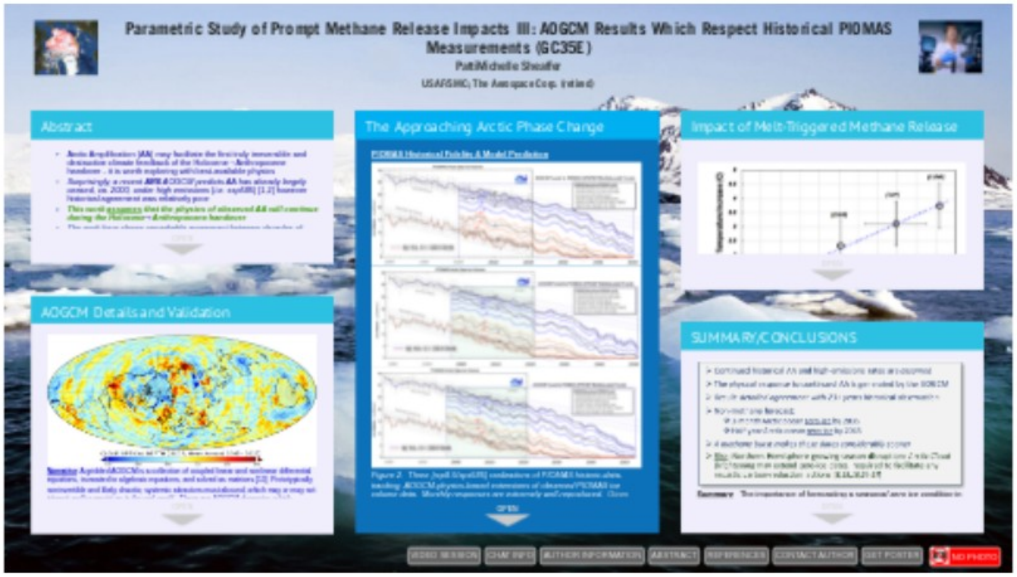
Parametric Study of Prompt Methane Release Impacts III: AOGCM Results Which Respect Historical PIOMAS Measurements (GC35E)



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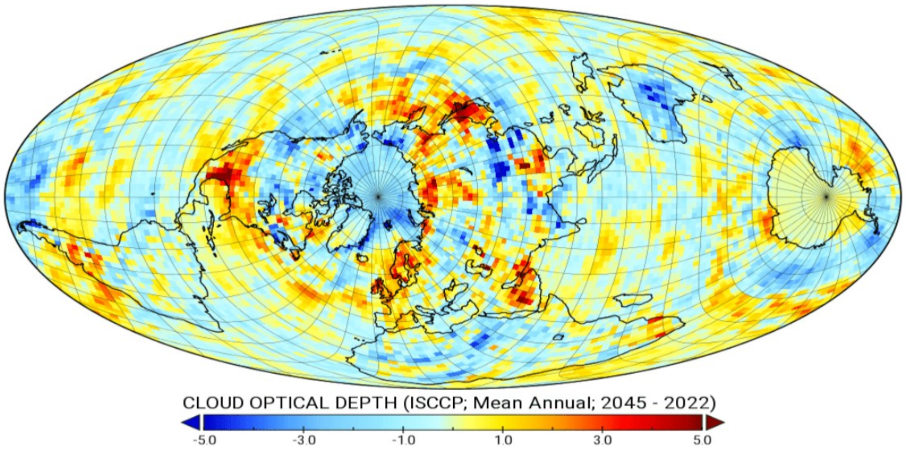
ABSTRACT/INTRODUCTION

- Arctic Amplification (**AA**) may facilitate the first truly irreversible and destructive climate feedback of the Holocene → Anthropocene climate handover (i.e., *climate breakdown*) – the proximity of this event is therefore worth describing with best-available physics and comparing to careful measurements
- Surprisingly, a recent AR6 AOGCM submission predicts AA has already largely ceased, *ca* 2000, under high-emissions (i.e. ssp585); however, agreement was relatively poor over the inappropriately short AR6 'historic' validation time scale of 15 years [1,2]
- This work *assumes* that the physics of both observed AA and observed RCP8.5 will continue during the Holocene → Anthropocene climate handover in the near-term (10–30 years)
- Herein, an AOGCM with a simple Arctic tuning is used to accurately reproduce PIOMAS historic data for a >20 year time period to support a more valid comparison with observed PIOMAS trends.
- The results of this externally-forced AA show *remarkable* agreement between decades of PIOMAS data and model predictions, usually within the 1-σ error bars of the PIOMAS data set.

A near-term Arctic Ocean ice melt AOGCM model prediction is made. Afterward, the impact of methane release from an Arctic shelf clathrate and/or permafrost-capped *natural gas province* is also estimated.[6-12,28,31] This work is not considered an incremental improvement on AOGCM model development and sophistication: The development cycle on AOGCMs is far too slow, given the evident rapid acceleration of heating and climate breakdown (wildfires, superstorms, crop failures, heat waves).

In order to provide appropriately rapid results, this work is a small tuning of an *existing* AOGCM. This tuning produces a remarkably detailed consonance with the PIOMAS data record over more than 20 years, and will soon be extended to the entire PIOMAS data record. (see *Appendix*) Thus, these results are a *physics-based*, *timely and reasonable* near-term prediction of the first Arctic Phase Change (**APC**), which is expected to have a massive impact on civilization. However, it is not clear how far beyond the near-term (e.g., *ca* 2040) these model parameterizations provide reliable predictions, especially given significant non-modeled feedbacks (e.g., Taiga snowline retreat, permafrost melt, snow darkening, etc.). Thus, the results presented here are likely a "best-case" scenario, with real world impacts and timelines considerably more constraining on civilization.

The cry for exceptional governmental action has seldom been clearer. This work was driven by the view that the sooner such these physics-supported near-term estimates are available, the better; this despite the ongoing lack of functional and appropriate climate rhetoric and action, as well as exploitation.



__Above__: Modeled changes in cloud optical depth between 2045 and 2022; image presented here to illustrate the AOGCM horizontal grid resolution.

AOGCM DETAILS AND VALIDATION

Narrative: *A gridded AOGCM is a collection of coupled linear and nonlinear differential equations which are truncated into algebraic equations, combined with various subgrid parameterizations, and then solved as algebraic matrices.[13] Prototypically noninvertible and likely chaotic; attractors must abound in the difference equations, which may or may not interact and/or persist in the same way as do real-world chaotic weather attractors. These are the AOGCM and real-world dynamics, which generally yield low agreement between different AOGCM models, but nonetheless dominate the large-scale atmospheric circulations in the real-world.[14,20] Large changes in these circulations will undoubtedly affect Northern Hemisphere (**NH**) food production, and are thus of grave concern, but, as mentioned, tend to be uncertain.*

Due to the above dynamical considerations, minimal model results beyond the Arctic itself are presented herein. We are also unaware of any accurate historical validations of AOGCMs to the near-term regional progress of the observed very rapid Arctic phase change. The primary value of the APC result relies upon highly-accurate model reproduction of the historic PIOMAS Arctic ice volume dataset using a simple, non-dynamic model tuning, coupled with the assumption of continued AA.

*The result of this work is particularly critical at this time during the Holocene → Anthropocene climate handover, as substantive global changes to emissions are not being undertaken, and large-scale planetary climate tipping points approach civilization unhindered. This work examines one fell example: **the Arctic phase change**.[3-5] It is likely that the Arctic phase change will produce a significant, temporally-localized acceleration in the rate of the Holocene → Anthropocene climate handover, possibly producing significant or fatal disruption of global civilization. Hence, regional **Arctic cloud brightening** [8,24-27] may "apply of the brakes" to the APC in conjunction with simultaneously accelerating the collapse process for global carbon-emission industries – both exceptional tasks.*

The AOGCM and its preparation was described previously [6] and is used for the calculations here. Following spin-up, it was tested for short-term stability and drift while held at constant 1997 (Figure 1).

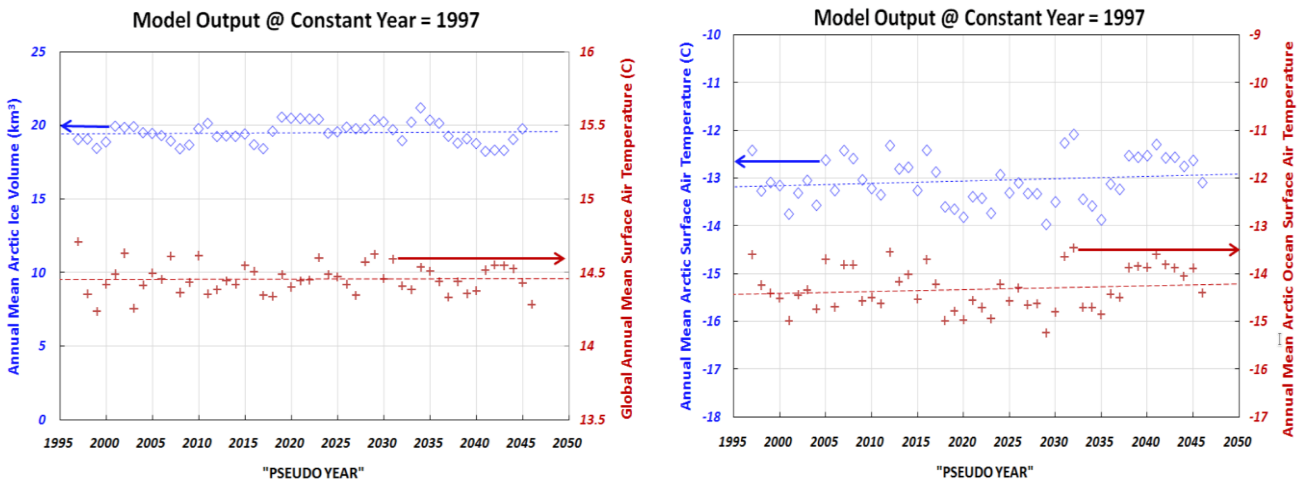


*Figure 1. AOGCM stability check run for **constant year 1997**, over time period of interest, after initial spin-up. All data demonstrate a mean drift rate less than 0.5% per year.*

The AOGCM was tuned to reproduce the PIOMAS historical data measurements, then integrated forward to produce an AOGCM-physics-based estimate of the near-future behavior of the Arctic basin ocean ice volume under these conditions. Details of Arctic Ocean ice thickness and area are avoided since the area/ice balance has a considerable dependency on model dynamics and is more uncertain.

The AOGCM Tuning was selected to avoid complex, localized, or ad hoc modifications to the existing and relatively well-understood AOGCM atmospheric parameterizations: Instead, a boundary-condition tuning method diverted a small fraction of global mean top of atmosphere (grid boundary; **TOA**) insolation to Arctic Ocean TOA insolation. The daytime Arctic basin TOA insolation was increased at a mean annual rate of about 83% of the latent energy needed to melt the PIOMAS-observed mean annual melt (0.4 $Wm^{-2}y^{-1}$).[7] In addition, a winter *nighttime* insolation energy input (~50 Wm^{-2}) was required in the Arctic Ocean to offset the model bias toward excessive Arctic ice refreeze under winter nighttime conditions. This was increased at the same mean annual rate.

Grid boundary insolation adjustments are disfavored by some researchers, although they are relatively straightforward and have the advantage, in the enforcement of the uncertain physics of AA, of providing a controlled energy input near the surface[8,20] and do not otherwise alter existing model grid-level parameterization schemes. Thus, AA is maintained under *thermodynamic* control and is more or less immune to uncertain future, poorly-modeled weather dynamics. It is noted that this particular tuning is not considered an advance in AOGCM science per se, but provides an immediate physics based, historically-accurate and results-focused Arctic phase-change prediction in the near term. This is crucial because integrity of civilization is rapidly undergoing challenge by the accelerating Holocene → Anthropocene climate handover, especially the food supply.[15-17] It is thought unlikely that time or resources are available for significant Arctic/AA model improvements before large, key responses must be implemented. Indeed, given the evident inertia, any physically-plausible responses to prevent Arctic summer phase change within the modeled near-term time scale seem extraordinarily difficult.

The estimated global mean surface air temperature rise during the modeled time period is shown in Figure 1a. Two interpretations are provided, an intersecting pair of lines and a parabolic fit. The contribution of the Arctic insolation heat to the global insolation heat input is very small and not directly associated with the modeled APC; nonetheless, the linear fits yield useful insights.

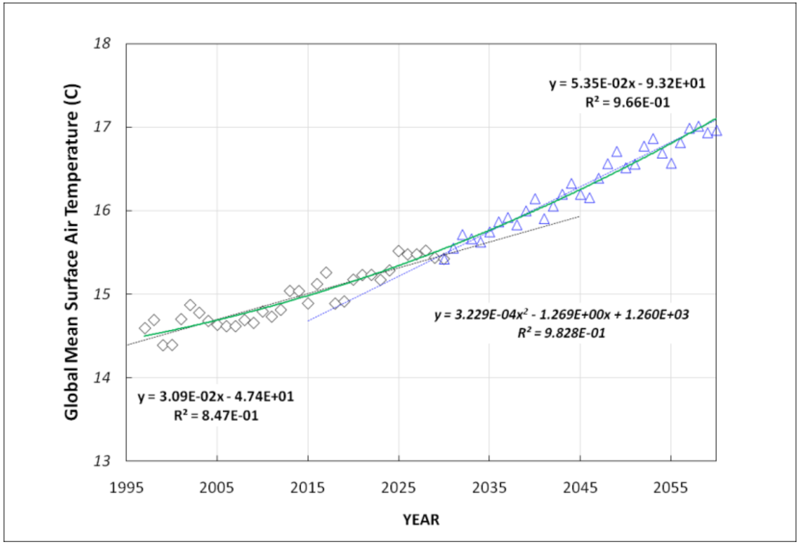


Figure 1a. Rapid acceleration in rise of global mean surface air temperature modeled in this work.

ARCTIC PERSISTENT SEASONAL PHASE CHANGE

PIOMAS Historical Fidelity and Model Prediction

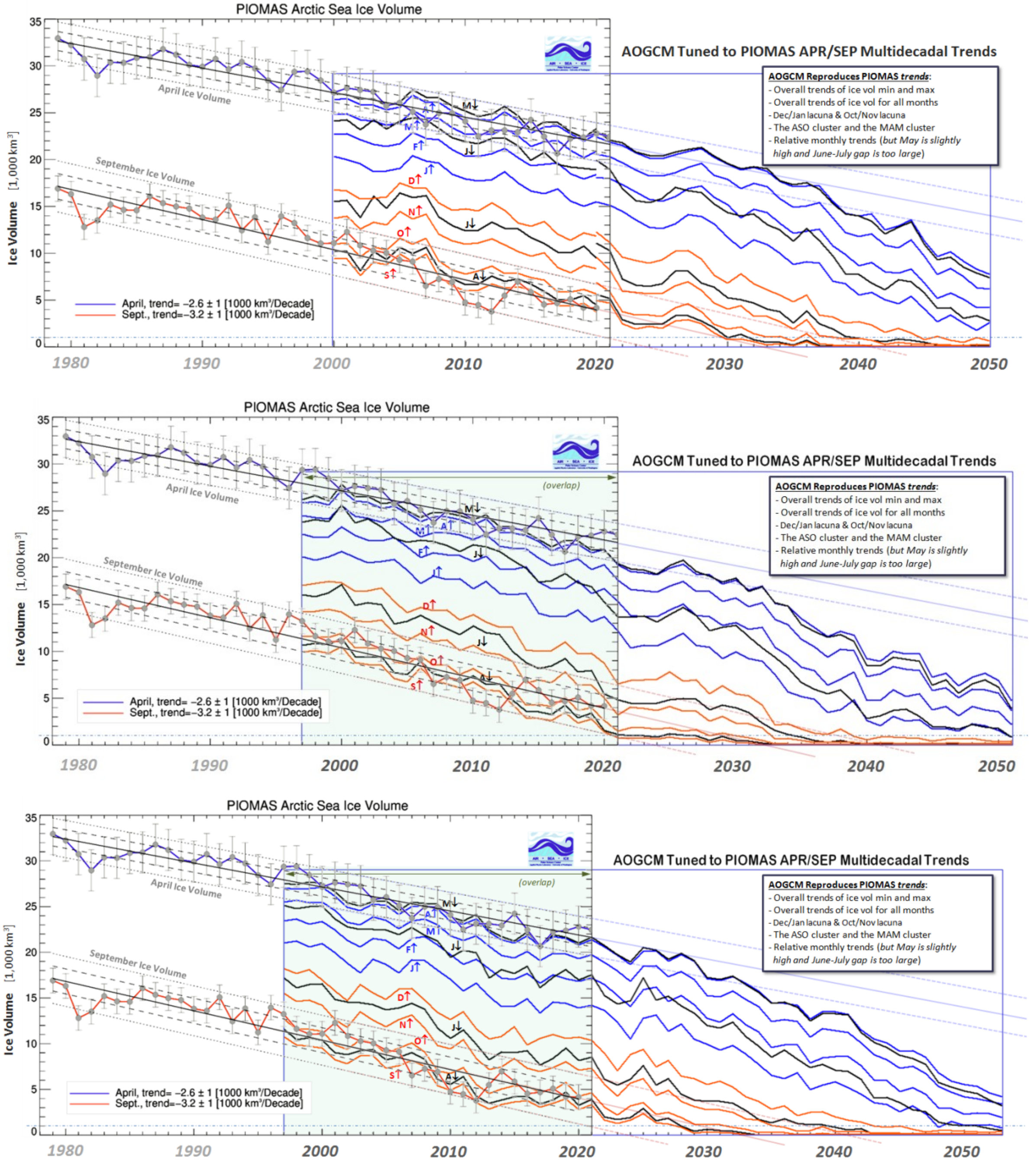


Figure 2. Three {rcp8.5/ssp585} realizations of PIOMAS historic-data-tracking by the AOGCM, along with AOGCM-physics-based predictive extensions of observed PIOMAS ice volume data. Monthly responses are extremely well-reproduced for over 2 decades. Given more model run-time, this simple tuning would produce detailed agreement with PIOMAS data over the entire PIOMAS dataset. The shown "historic" period overlaps with model calculations - 1997 to 2021. Summer-season APC is predicted to be complete ca 2035, and half-year APC 2040 - 2050. Impacts on Northern Hemisphere growing seasons are therefore a serious and proximate concern. ***(Compare with Figure 1a)***

The historical modeled September and April ice volume realizations shown in Figure 2 lie within the monthly 2-σ scatter provided by the PIOMAS data set throughout the period investigated. The monthly 1-σ scatter data are compared in Figure 2a. Other features of consonance between PIOMAS and the model are indicated. *The modeled monthly agreement and temporal accuracy with respect to PIOMAS is remarkable*. An obvious feature shared by all realizations in Figure 2 is that winter seasonal ice melt begins to accelerate significantly when the ASO (August-September-October) seasonal APC is nearly complete. Physically, this may relate to what is essentially the vanishing of a "virtual" latent-heat reservoir (i.e., mass of summertime ice available to melt in response to atmospheric warming), which had been historically present in ASO, but will become permanently unavailable, and that unavailability will expand into other seasons. This will yield an exclusively *sensible-heat* reservoir being present for increasing portions of the year (i.e., warming water/atmosphere, cf. Figure 3).

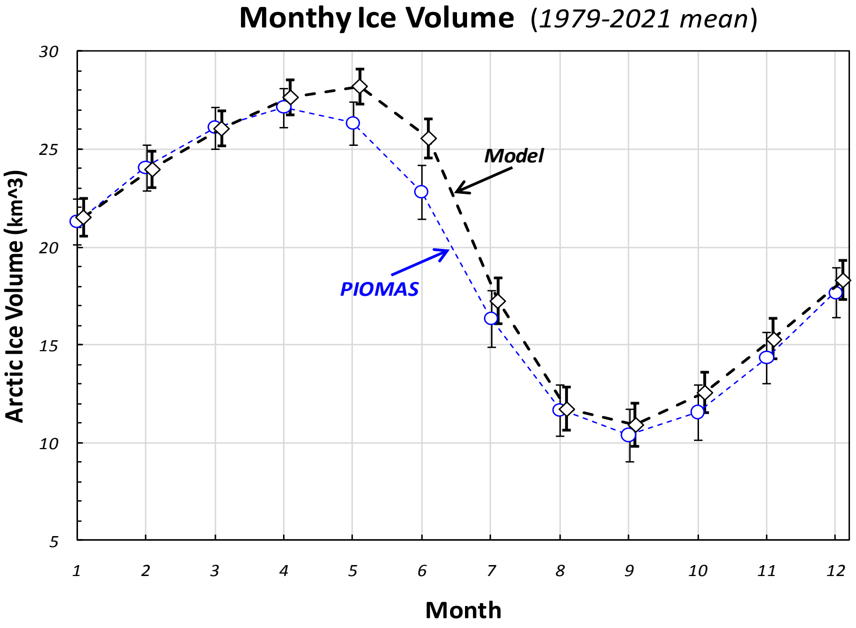


Figure 2a. Detrended (historic; 1979-2021) Arctic ice volume monthly means for PIOMAS data and one realization of the AOGCM calculations contained herein. ***Circles****: PIOMAS data;* ***Diamonds****: model (1-σ monthly annual scatter bands indicated by error bars). The generally smaller error bars for the model outputs indicate slightly less temporal variance over the modeled 1979-2021 time period than is seen in the PIOMAS data. The MAY-JUNE ice volumes are overpredicted (excess sea ice volume) despite the AA inputs, but are nonetheless within 2σ of the PIOMAS data. All other monthly data (PIOMAS and model) are within 1σ of each other over this time period.*

The three realizations provided in Figure 2 demonstrate, from top to bottom, progressively larger modeled effects of AA. The large natural variability over the 23-year PIOMAS historical overlap period makes it difficult to know which realization is most representative, so new integrations spanning all 40 years of PIOMAS data are underway.

Note that it can reasonably be argued that AOGCM simulations have always *under*-predicted the global changes from the Holocene → Anthropocene climate handover, suggesting that the most aggressive simulation, at the bottom of Figure 2, should probably be considered most reliable of the three, from the perspective of real-world changes. Also note that most known concurrent warming feedbacks are not included in AOGCMs – hence all the Figure 2 predictions are likely *overly*-optimistic. Some details from the third realization in Figure 2 are presented below.

As indicated in the ***Narrative***, global circulation *dynamics* are not modeled accurately, so predicted global weather pattern changes resulting from Arctic phase change are of relatively low reliability and not extensively pursued here. On the other hand, it is generally understood that the localized Arctic modeled responses, being dominated by Arctic thermodynamics, are inherently more reliable, and are the focus of the data presented below. [14,18,19]

Despite the global weather pattern results not being presented, the modeled Arctic responses are understood to have driving implications for global weather patterns in the real world, such as the role of the equatorial/Arctic temperature gradient in driving jets and the westerly atmospheric flows. In this regard, the Arctic 500 mb height data presented in Figure 6 suggests slowing of the jets and Westerlies, and perhaps repeated disruption of the jets, impacting NH seasonal agriculture. The model results thus reveal the temporal proximity of potential disaster.

Due to dynamic uncertainties, the modeled global results of Arctic phase change are not presented, except for one attempt to forecast changes in long duration precipitation events (**LDE**) over continents (Figure 7).[20]

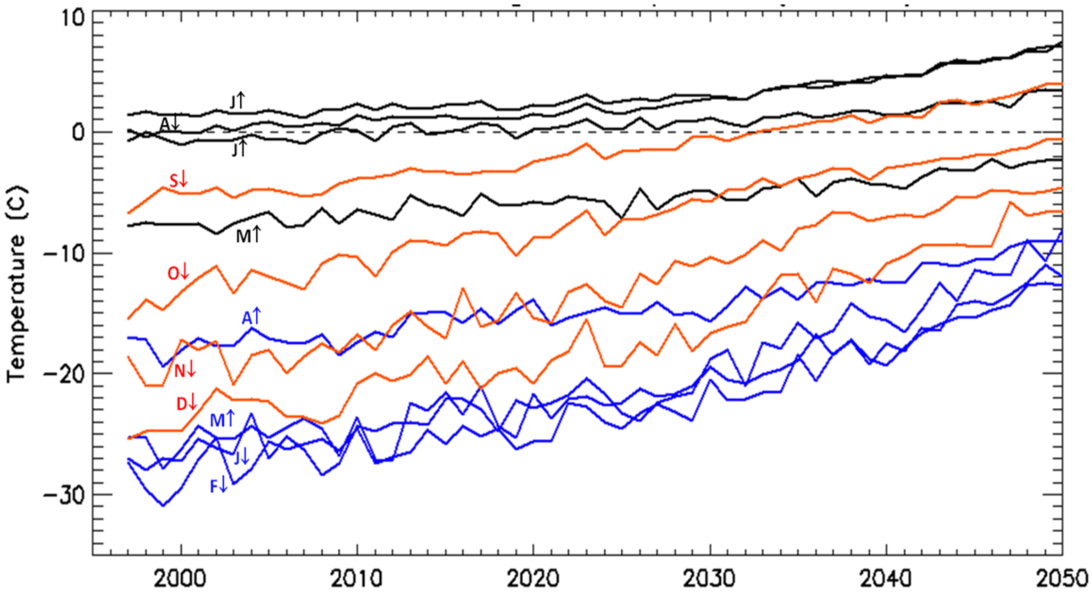


Figure 3. Monthly mean Arctic Ocean surface air temperature.

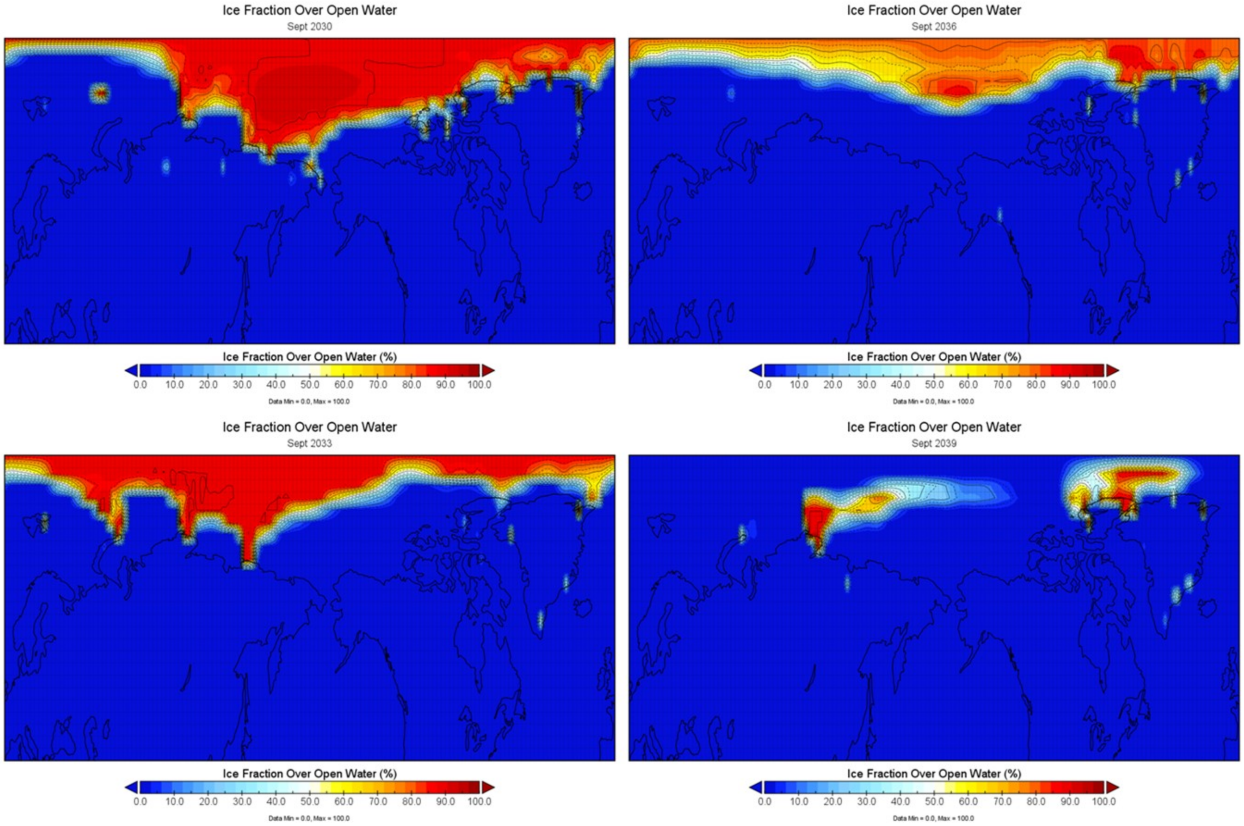


Figure 4. Ice geometry predictions (surface area and thickness) are much less reliable than predictions of ice volume (Figure 2), the latter of which is more closely tied to Arctic thermodynamics. Thus, the ice-fraction shown here only crudely illustrates expected changes. (Also, note the representational-biases of the map projection used here.)

The mean annual Arctic Ocean "freeze/thaw line" (surface temperature at 0^oC) is shown in Figure 5. The freeze line (darkest blue) is observed to move poleward until merging with the pole in about 2040, then vanishing before 2050. Note that in Figure 3 it is shown that the Arctic Ocean monthly mean surface air temperature is increasingly near or above freezing for several months of the year after 2030.

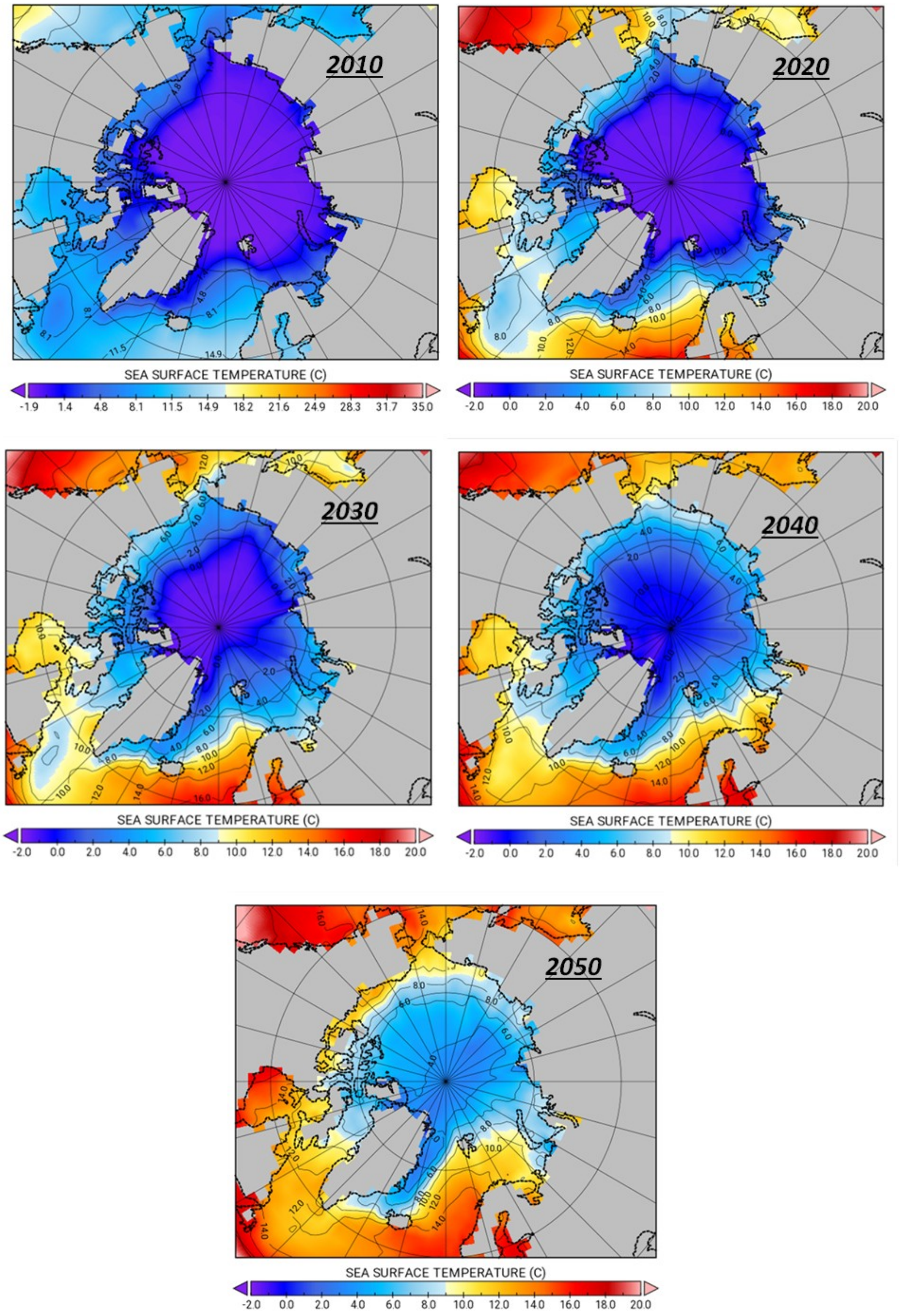


Figure 5. Modeled annual mean sea surface temperature in selected years over the time period investigated. The migration of the mean annual surface 0^{o}C location can be observed to move poleward until ~2040, and then disappear by 2050.

<u>The mean annual Arctic 500mb height</u> (Figure 6) is associated with the strength of the Westerly flows and jets. Decreased westerly flows and jet disruption are suggested by the modeled APC. Such atmospheric model dynamics (detailed, day-to-day models of jets, Westerlies) are unreliable and not explored here despite the importance of changes in the equatorial/Arctic gradient.

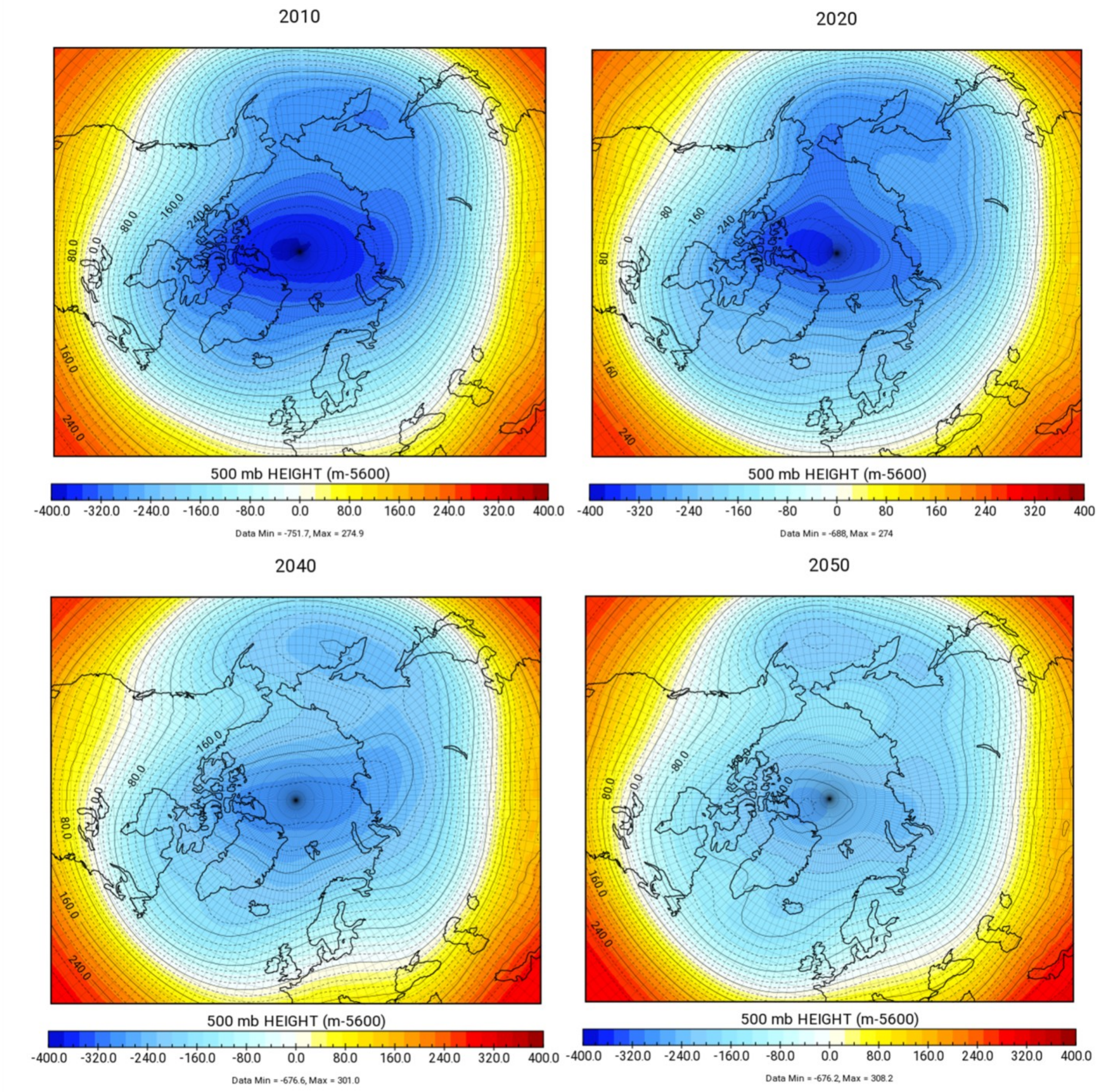


Figure 6. Modeled annual mean 500mb height in the Arctic, modeled-historical (above) and predicted (below).

<u>Long duration precipitation events</u> (LDE) are one suggested metric for detecting changes in the geostrophic Westerly flow and/or changes in the flow of Jets.[20,21] Since these are controlled by global model dynamics, there are *significant* uncertainties involved. In Figure 7 is plotted the number of 5-day LDE precipitation events – defined as 5 consecutive days with grid-level precipitation above 5 mm per day. Unfortunately, these are low-confidence predictions given the uncertainties of modeling global dynamics.

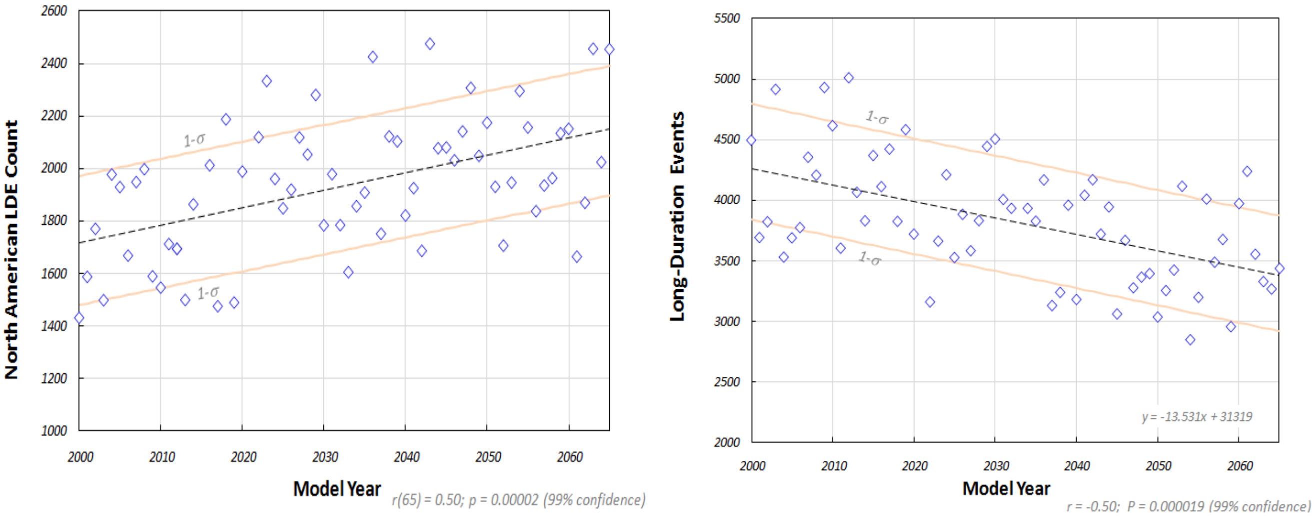


Figure 7. Annual global cumulative number of 5-consecutive-day events per year having grid-resolved precipitation above 5 mm/day. ***Above****: grid region = 76W-126W by 30N-60N (North America);* ***Below****: grid region = 10W-45E by 30N-60N (Europe). The p-value suggests reasonable statistical confidence; however, direct AOGCM predictions of regional precipitation, which are controlled by the dynamics of the large-scale atmosphere, are subject to considerable uncertainty in AOGCM models. [14,18-20]*

MODELED IMPACT OF MELT-TRIGGERED METHANE RELEASE ON APC

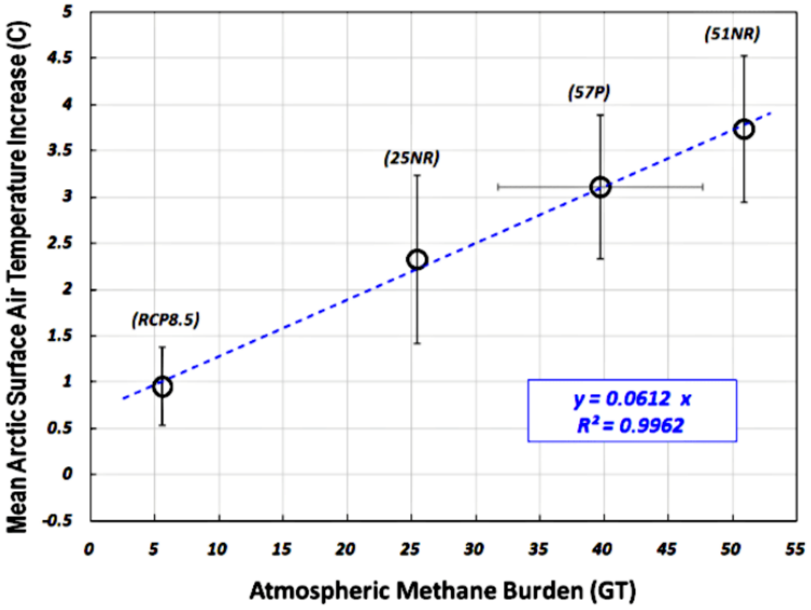


Figure 12. Arctic (68°N – 90°N) mean surface air temperature rise above mean of 2020-2025 Arctic temperatures, for all scenarios. Y-axis 1-σ error bars represent combined annual model variation and the observed upward drift of each scenario over that time period. The single X-axis 1-σ error bar represents the exponential decrease in methane burden as the 51P scenario decays back toward RCP8.5 (see Figure 5.). Temperature rise is roughly double that of the mean global surface air temperature rise.

Figure 8. Previously modeled Arctic response to several methane burst scenarios taken from Ref. [6] ***Example****: A methane burst yielding a total of a 20 GT atmospheric methane burden would rapidly increase Arctic surface air temperature by ~1^{o}C.*

Although controversy still exists, rapid methane releases from shallow continental-shelf methane clathrates in a seasonally ice-free Arctic ocean are of concern, and some have been measured.[8-12] Likewise, Arctic permafrost-capped *natural gas provinces*, which may be un-capped by melting permafrost, have also been observed.[28,31] The potential impacts of a sudden methane release were applied to the results already presented here by using an offline method – that is, not included in the numerics of the AOGCM model itself. Instead, the timings of the model results are adjusted after the runs, to provide estimates based on previously-modeled methane-induced Arctic Ocean basin surface air temperature increases (Figure 8).[6] Acceleration of the APC is estimated by using Arctic ocean basin surface air temperature as a guide to adjusting the results of the runs (Figure 2) to the accelerated timing of ice-free conditions (from [6]).

The real-world interactions between AA itself and the methane burden are not well understood. Depending on the total increase of the atmospheric methane burden from such a release, and the timing of such a burst event, the Arctic phase change may be accelerated by as much as 8 years (Figure 10). For these estimates, it is assumed that the sudden methane increase occurs starting in 2029. Note that the methane model in Ref. [6] assumes a globally uniform increase in methane burden; however, an Arctic-localized methane release could accelerate these times still further by increasing the observed AA.

Two examples are shown in Figures 9 and 10. Again, such changes likely pose a serious concern for NH seasonal food production since the major changes in Arctic temperature patterns occur during the NH growing seasons. These scenarios result in half-year APC occurring by the mid-2030's with nearly complete non-winter phase change by *ca*. the 2050's.

It must be emphasized that these are estimates most reliable for the *near term* based on an *offline* comparison to the modeled data presented here (Figure 2), AA continuing at historic rates, a continued high carbon-emission scenario, and the rate of Arctic warming modeled in ref. [6].

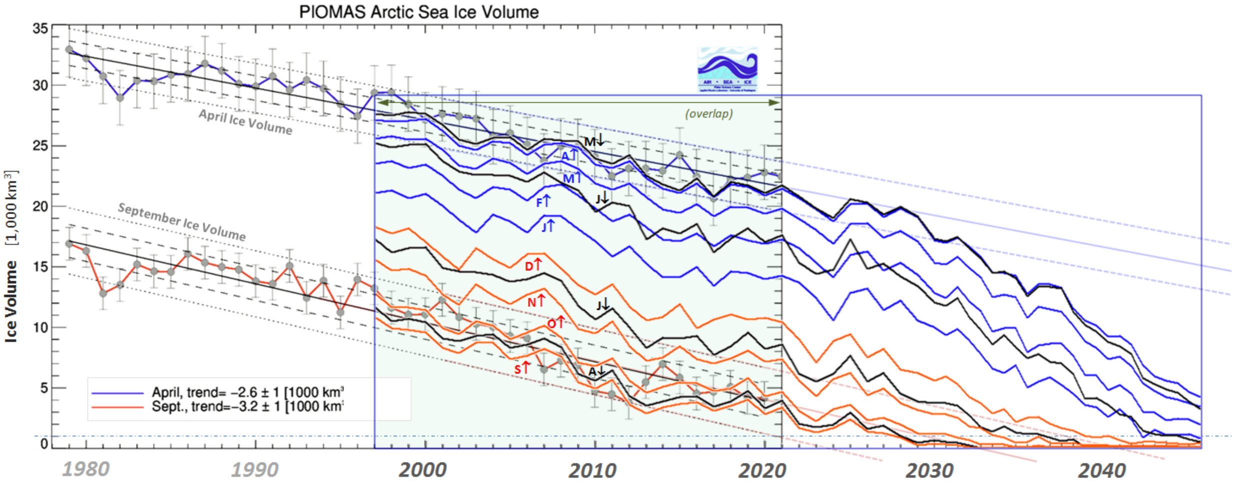


Figure 9. Accelerated ice melt estimates, using the (non-methane) model outputs shown in Figure 2, and assuming ~1 °C increase in Arctic temperatures suggested by Figure 8, for a ~20 GT total atmospheric methane burden (also assumes AA continues at approximately the historically observed rates).

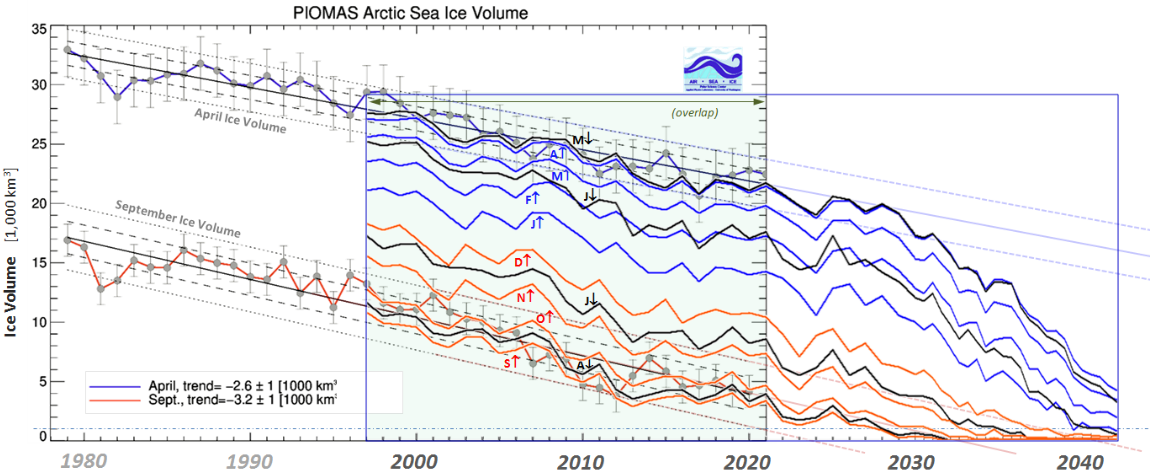


Figure 10. Accelerated ice melt estimates, using the (non-methane) model outputs shown in Figure 2, and assuming ~2.5 °C increase in Arctic temperatures suggested by Figure 8, for a ~45 GT total atmospheric methane burden (also assumes AA continues at approximately the historically observed rates).

SUMMARY/CONCLUSIONS

- **Continued historical AA and GHG increases are *assumed* AOGCM inputs here**
- **Future Arctic *physical response* to AA and GHG increase is calculated by the AOGCM**
- **Detailed agreement with 20+ years of Arctic sea ice mass observations**
- **Non-methane forecast:**
  - *3-month Arctic Ocean zero-ice by ca 2035*
  - *Half-year Arctic Ocean zero-ice by ca 2045*
- **Risk: Northern Hemisphere growing season disruption**
  - *Arctic Ocean Cloud Brightening may extend modeled zero-ice dates [6]*
  - *Probably required to facilitate any realistic carbon-reduction actions [8,15,16,24-27]*
- **Large methane release (clathrates/provinces) moves estimated APC dates considerably sooner than modeled here**

Summary Narrative *The extreme risks involved with permanently removing the entire Arctic ice mass from the NH climate system underscores the importance of forecasting the approaching seasonal zero-ice condition in the Arctic (ca 2035). Among presumed risks is the significant potential for periodic disruption of NH food production, which already has a decreasing trajectory, as well as increased extreme heat waves.[15-17] Based on previous work, it is estimated that if large scale seasonal Arctic ocean warming and permafrost melt could facilitate a rapid increase in the atmospheric methane burden[6,8-12,28,31], the model-estimated dates for Arctic phase changes could be accelerated to 2030 and 2038, respectively. Even in the absence of a methane burst, the modeled acceleration of global temperature rise by loss of a seasonal sea-ice cover concomitant with the onset of APC (i.e., Figure 1a) is of concern. The Arctic Ocean is therefore suggested as a rational target for a "minimally-damaging" geoengineering effort such as Arctic Ocean cloud brightening, to attempt to stave off seasonal Arctic ice clearance and maintain the NH food-production basis for global technological civilization needed to respond to the Holocene→Anthropocene climate handover.[8,24-27] AOGCM estimates of the impacts of insolation reduction were previously made.[6] Unfortunately, any putative geoengineering effort is likely useless without a concurrent global halving of industrial, power generation, and transportation output.[29,30]*

In this work, continued Arctic Amplification (AA) and RCP8.5/ssp585 emissions rates were assumed for the near-term. This assumption is consistent with measured carbon release rates.

Some AR6 model contributions suggest that AA ceased ca. 2020 – but these tend to poorly reproduce historical PIOMAS trends over the AR6 "historic" interval, which appears too short to provide high confidence given the variances of model results and the PIOMAS dataset.[1,2] This work, examined an up-to 24 year long historic interval, found exceptional agreement between modeled results and the PIOMAS data. This interval is currently being extended to 40 years (see Appendix).

Lastly, in this work, AA is enforced and tuned to the PIOMAS historical record by moving a small fraction of global TOA insolation to Arctic Ocean basin TOA insolation – avoiding localized grid-level atmospheric parameterization changes to obtain Arctic warming (e.g., cloud-model top-height adjustments). This maintains Arctic Ocean surface warming under thermodynamic control rather than control of the dynamics of the atmosphere (atmospheric rivers, weather events, etc.), as is appropriate in the mean for the Arctic Ocean basin region.

*** ***The author expresses her gratitude to the dedicated scientists at GISS for outstanding software.****[22,23]* ***

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APPENDIX

(22June2022)

Due to a lack of resources, the data presented in this paper did not include a model integration of the entire PIOMAS historic record into the future. Given the simplicity of this approach to AA modeling, it was considered a small thing (although computationally expensive) to extend the integrations to the entire PIOMAS historic region and into the future, considered useful to demonstrate the utility of the model approach used herein. This work has recently begun, and a first demonstration is presented below in Figure A.1. The results indicate that Arctic Amplification (AA) continuing as anticipated will have the result that a summer season Arctic phase change should be anticipated shortly – most likely ca. 2030 (cf. Figure 2). *It should again be stated that important warming feedbacks, such as snow albedo change and Taiga/Arctic snow line retreat, have not been adequately included in AOGCMs, suggesting seasonal Arctic phase change will likely occur sooner than this estimate*.

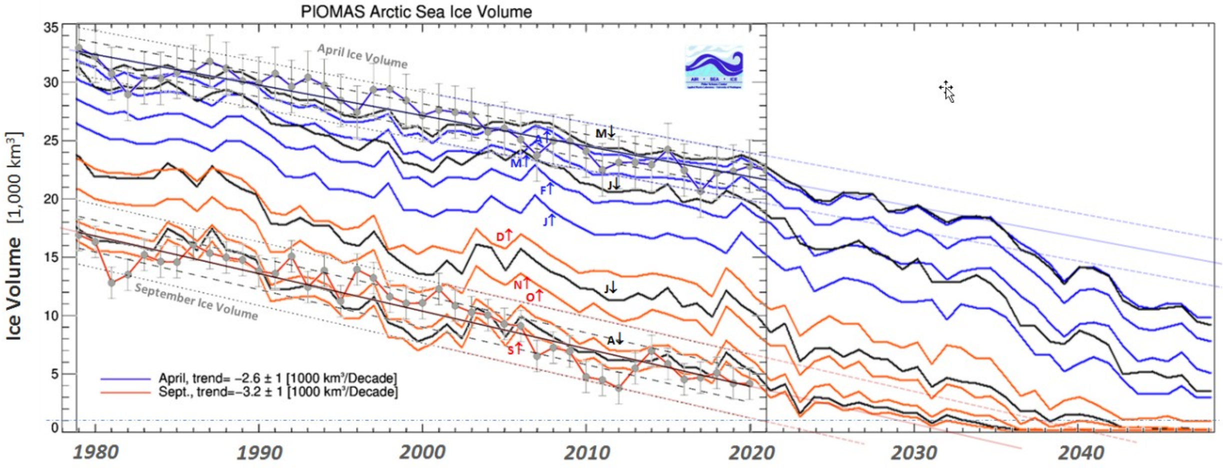

Figure A.1. Monthly Arctic phase change ice-volume profile results overlaid on the PIOMAS historic means for April and September, under conditions of continued observed linear rates of Arctic Amplification (AA) and the observed RCP8.5 scenario. The more proximate result, presented earlier in Figure 2, is therefore demonstrated to be consistent with this result reproducing the entire PIOMAS record. It should be noted that given the shallow rates of the PIOMAS historic trend and the trends modeled here, the exact value of the PIOMAS summer trend has a large impact on the prediction of recurring summer zero-ice conditions. It should also be noted that important warming feedbacks are not included in this AOGCM. Summer-seasonal ice-free conditions are anticipated to destabilize geostrophic flow patterns during the Northern Hemisphere growing seasons.