COMMENTARY:

Influence of internal variability on Arctic sea-ice trends

Neil C. Swart, John C. Fyfe, Ed Hawkins, Jennifer E. Kay and Alexandra Jahn

Internal climate variability can mask or enhance human-induced sea-ice loss on timescales ranging from years to decades. It must be properly accounted for when considering observations, understanding projections and evaluating models.

A broad range of evidence shows with high confidence that human-induced climate warming has driven a decline in Arctic sea-ice extent over the past few decades[1]. However, the rate of sea-ice decline has not been uniform. Arctic sea-ice extent was lost at a considerably higher rate from 2001–2007 than in the preceding decades (Fig. 1), which caught the attention of scientists and the public alike[2]. In contrast, from 2007–2013 there was a near-zero trend in observed Arctic September sea-ice extent, in large part due to a strong uptick of the ice-pack in 2013, which has continued into 2014. By deliberately cherry-picking these periods we will demonstrate how using short-term trends can be misleading about longer-term changes, when such trends show either rapid or slow ice loss.

The possibility that internal climate variability can produce decade-long periods in the twenty-first century featuring enhanced[3] or negligible[4] sea-ice loss is well documented in the scientific literature[3–5]. Broadly communicating this role of internal climate variability on sea-ice trends to society at large is key, as in the case of temperature and precipitation changes[6–8]. Yet the lack of a significant sea-ice trend since 2007 is causing some in the media to question the scientific understanding of climate change[9], amplifying the scepticism which has garnered support due to the recent slowdown in global-mean surface temperature rise[10].

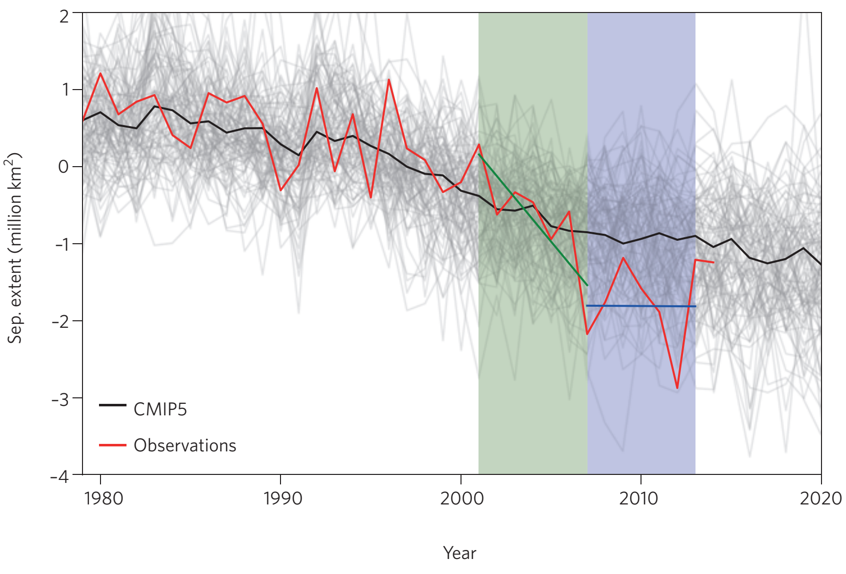

Figure 1 | Arctic September sea-ice extent anomalies. Sea-ice extent anomaly relative to 1980–2000 from observations (red) and 102 realizations from 31 CMIP5 models (grey), along with the CMIP5 ensemble mean (black). Linear trends are fitted to the observations over 2001–2007 (green) and 2007–2013 (blue). The CMIP5 ensemble mean is calculated such that each model has a weight of 1. Observations extend to 2014.

By others it is held that the periods of observed dramatic ice loss show that climate models are too conservative and significantly underestimate the observed sea-ice trends[11]. Proponents of this view often use extrapolation of historical trends to predict summer ice-free conditions in the Arctic as early as 2015, and much sooner than anticipated by the process-based models[11,12]. Just how likely were the recently observed sea-ice trends? Do climate models underestimate the historical trend, and what are the implications for the future?

Likelihood of recent observed trends

How likely is a 7-year period of near-zero trend in September Arctic sea-ice extent, as observed between 2007 and 2013? To answer this question we examine trends in Arctic sea-ice extent for all 7-year periods between 1979 and 2013 in the observations and in 102 realizations from 31 Coupled Model Intercomparison Phase 5 (CMIP5) global climate models (see Supplementary Information). If there was no long-term background trend in sea-ice extent we would expect random variability to lead to positive 7-year trends about 50% of the time (or with a probability $p = 0.50$). Alternatively, if internal variability was small compared to the background trend we would expect 7-year positive trends to be rare. In the model simulations of the past 35 years a 7-year period where a September extent trend was greater than or equal to zero occurs with a probability of $p = 0.34$ on average across the models (Fig. 2a). Thus, according to the models there is about a one in three chance of a 7-year period with a positive sea-ice trend, despite strong anthropogenic forcing.

For comparison, the enhanced rate of sea-ice loss observed from 2001–2007 occurs with a probability $p = 0.05$ on average in the model simulations. This result suggests that such a period of enhanced

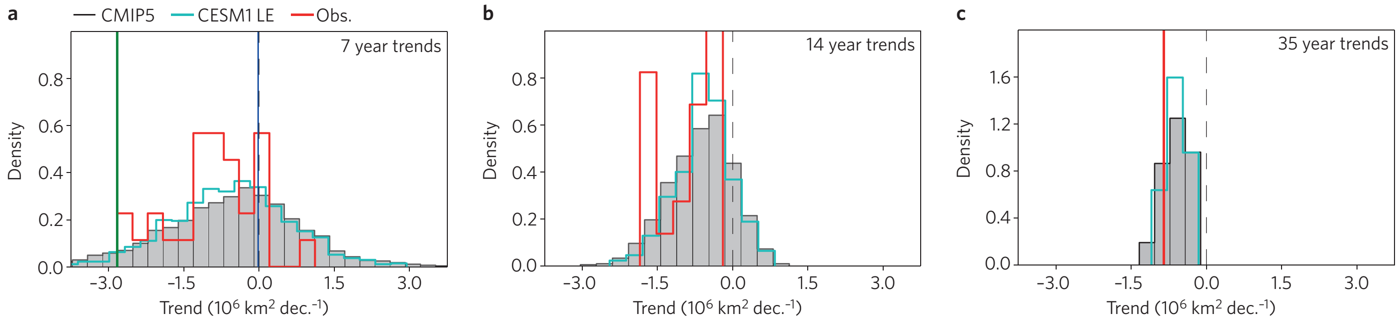

Figure 2 | Arctic September sea-ice extent trends. **a,** Distribution of all possible 7-year trends between 1979–2013 for observations (red), the CMIP5 realizations (grey) and the 30 CESM1 LE realizations (cyan). **b**, As in **a** but for 14 year trends. **c,** As in **a** but for 35 year trends. The solid green and blue lines in **a** are the observed linear trends from 2001 to 2007 and 2007 to 2013, respectively. Density implies that the area under each distribution equals one.

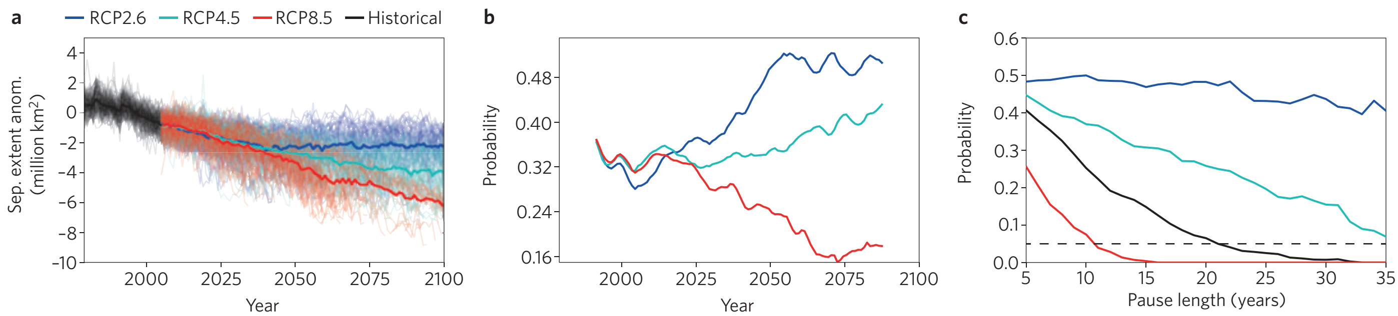

Figure 3 | Probability of a pause in September Arctic sea-ice extent. **a**, September Arctic sea-ice extent anomaly relative to the 1980–2010 period for the CMIP5 models historical and three RCP experiments. **b**, Probability of a 7-year pause over a 21 year rolling window. **c**, Probability of a pause as a function of pause length in the Historical-RCP4.5 experiment over 1979–2013 (black), and in the future over 2066–2100 under the RCP2.6 (blue), RCP4.5 (cyan) and RCP8.5 (red) experiments. The horizontal dashed line represents a probability of $p = 0.05$. A pause is a period with a trend ≥0. Only ice extents $\geq 1 \times 10^6$ km² are considered.

loss, while rare, is plausible given our best understanding of the climate system, which is embodied within climate models, and the broad sampling of internal climate variability that this large ensemble of simulations provides. These probabilities of a 7-year period featuring a pause or enhanced ice loss are not sensitive to the historical mean sea-ice extent or its variance, even though these properties vary significantly amongst the CMIP5 models (Supplementary Information).

The spread in the distribution of CMIP5 trends arises due to a combination of inter-model spread and internal variability. To help isolate the influence of internal variability alone we turn to the Community Earth System Model 1 Large Ensemble (CESM1 LE), which comprises 30 realizations from a single model[13]. It's striking that the spread of trends in the CESM1 LE is similar to that in CMIP5 (Fig. 2a), indicating an important role for internal variability in determining the CMIP5 spread (Supplementary Information). The chance of a 7-year pause in sea-ice loss occurs with a probability $p = 0.32$ in CESM1 LE, similar to the CMIP5 result (Fig. 2a). The enhanced rate of sea-ice loss observed between 2001 to 2007 occurs with a probability $p = 0.03$ in the CESM1 LE simulations, confirming the notion that it is a rare event but plausibly driven by internal variability. Thus, both the enhanced sea-ice loss during 2001–2007, and the recent period of near-zero trend are consistent with the supposition of internal climate variability onto the background of long-term radiatively forced sea-ice decline as simulated by the two model ensembles, and in agreement with previous work[4,14].

Despite the strong influence of internal variability, such short historical trends are often used to comment on the likely future trajectory of Arctic sea ice. In the CMIP5 models short-term (for example, 7 year) trends over the historical period and the future long-term trend over 2013—2070 show no significant correlation at the 5% level (see Supplementary Information). These models thus suggest that there is no reason to consider the dramatic ice loss from 2001–2007 or the period of zero trend since 2007 to be a harbinger of future long-term changes in Arctic sea-ice extent.

In moving from 7- to 14-year trends, the trend distributions narrow significantly, converging towards the background response to anthropogenic forcing (Fig. 2b). Yet, the spread of trends remains similar across the CMIP5 and CESM1 LE ensembles, indicating a continued role for internal variability. A period of positive sea-ice extent trends extending for 14 years has a probability of $p = 0.15$ according to the average of the CMIP5 simulations ($p = 0.14$ in CESM1 LE). It is thus quite conceivable that the current period of near-zero sea-ice trend could extend for a decade or more due solely to internal climate variability masking the anthropogenically induced decline.

Simulated trends versus observations

Previous studies have indicated that the multi-model mean long-term September sea-ice extent trend is smaller than observed[1,15]. The observed trend reflects both the forced response of the system to anthropogenic influence as well as internal variability, even when considering multidecadal timescales[1]. In the model ensemble mean the influence of internal variability has effectively been averaged out and the trend mostly reflects the true model response to external forcing. Thus, there is no reason to expect the observed trend to fall on the model mean, even given perfect models. Similarly, the fact that the observed trend falls outside the given confidence interval of many

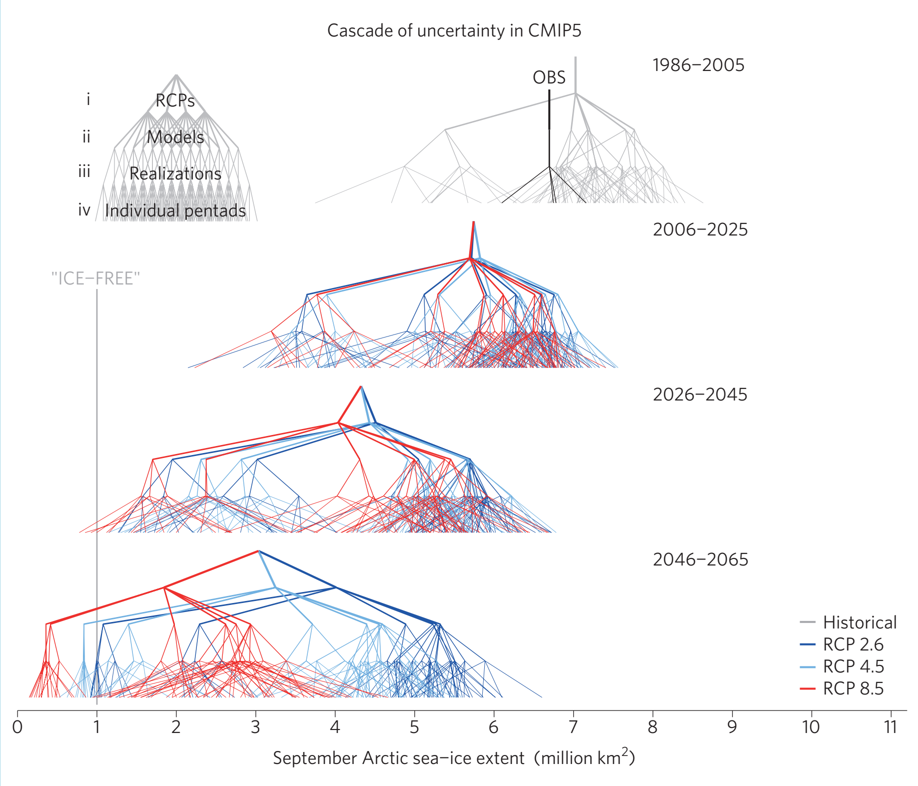

Figure 4 | Cascade of uncertainty in CMIP5. September sea-ice extent is shown at four different levels of averaging (top left). i, The multi-model mean from three experiments (RCP2.6, 4.5 and 8.5), representing emissions scenario uncertainty. ii, The multi-realization mean from each of six models, representing model uncertainty. iii, The time-mean for each realization available. iv, For pentads (5-year means) from each realization, which along with iii represents internal climate variability. See Supplementary Information for a list of models used. Note that the range of extents in the full CMIP5 ensemble is considerably larger than for the six models shown here.

individual model realizations is often taken as evidence that the models underestimate the observed trend[11,15]. However, trends in the observations and individual model realizations may differ significantly due to random differences in internal variability, rather than differences in the true response to external forcing[16,17].

Here we compare the observed long-term trend over 1979–2013 (35 years) with the full distribution of trends simulated by the many individual model realizations which include internal variability (Fig. 2c). This shows that the observed trend falls well within the distribution of simulated trends, lying at the thiteenth percentile of the CESM1 LE distribution and at the twentieth percentile of the CMIP5 distribution. For CMIP5 the spread of trends arises due to internal variability and inter-model spread. To properly account for both of these sources of uncertainty, we apply a carefully designed statistical test with the null hypothesis that the observed and simulated trends are equal (Supplementary Information). With p-values of 0.075 for the CMIP5 ensemble and 0.19 for CESM1 LE we cannot reject the null hypothesis at the 5% level for either set of models. Therefore, when accounting for internal variability, long-term trends in September Arctic sea-ice extent do not support the conclusion that the models, as a group, systematically underestimate the response to anthropogenic forcing.

Likelihood of sea-ice extent pauses

The probability of a pause in September sea-ice extent changes in the future, largely because of changes in the background anthropogenic trend. This also means that future probabilities depend on the emissions scenario. The strong mitigation of emissions under Representative Concentration Pathway (RCP) 2.6 reduces the long-term trend in September sea-ice extent (Fig. 3a). As the long-term trend reduces, the probability of a 7-year pause increases, and approaches $p = 0.5$ after about 2050 when the average long-term trend becomes near zero (Fig. 3b). Similarly, the probability of a pause increases towards the end of the century under RCP4.5. In contrast, under increasing emissions in RCP8.5 the long-term decline in Arctic sea-ice extent accelerates over the next few decades and then begins to level off towards the end of the century (Fig. 3a). As a result the probability of a pause under RCP8.5 reduces sharply until about 2075, after which it holds roughly constant near $p = 0.16$ (Fig. 3b).

Pause lengths of up to 32 years are seen in the CMIP5 ensemble over 1979—2013, and pauses of 20 years or less occur with $p > 0.05$. Pauses of longer duration become more likely towards the end of the century under RCP2.6 and RCP4.5 (Fig. 3c). Under RCP2.6, even pauses of 35 years occur with a probability $p > 0.4$ in the CMIP5 simulations over 2066–2100. Under RCP8.5, pauses of all lengths become less likely over 2066–2100 than they were in the historical period. Clearly the emissions scenario is an important factor in the future evolution of Arctic sea-ice, which we now consider in more detail.

Implications for future Arctic sea ice

How important is internal variability in model projections of future sea-ice extent, relative to other uncertainties? To visualize this we use an 'uncertainty cascade'[18] (Fig. 4) to show the mean sea-ice extent during four different 20-year periods and for the 6 CMIP5 climate models that have multiple realizations for each scenario and at least one pentad overlapping the observations (see Supplementary Information). The cascade represents the uncertainty due to the choice of emissions scenario, model, realization, and pentad (5-year mean) in descending order from the top, for each period.

Future human emissions are highly uncertain, and lead to an inter-scenario range in mean sea-ice extent that grows with time (as shown by the different colours), reaching about 2 million km^2 over 2046–2065 (1.3 million km^2 across the full CMIP5 ensemble). Model uncertainty in mean sea-ice extent over 2046–2065 is even larger with an inter-model extent range of 3.5 million km^2 averaged across scenarios for the six models shown in the cascade (9.4 million km^2 across the full CMIP5 ensemble). Even though the ensemble sizes of these six models are small (between three and six realizations), our characterization of model uncertainty using the inter-model spread is robust (see Supplementary Information).

In the cascade, internal variability is represented by the range between different realizations from the same climate model

(Fig. 4) and for the 2046–2065 period this range is 0.5 million km^2 on average across models and scenarios (0.6 million km^2 across the full CMIP5 ensemble; also see Supplementary Information). Internal variability on even shorter timescales, shown in the cascade by the range of pentads of a single realization, is 1.4 million km^2 on average, and reaches up to 4.6 million km^2. Variability in 5-year means is largest when the sea-ice extent reaches near ice-free levels. This pattern is most clearly shown using the CESM1 LE, in which variability increases as the sea-ice retreats, before dropping to close to zero when ice-free conditions are reached (Supplementary Fig. 6).

For the 20 year mean sea-ice extents over 2046–2065, model uncertainty is the dominant term (CMIP5 range of 9.4 million km^2), followed by scenario uncertainty (1.3 million km^2) and then internal variability (0.6 million km^2). It is worth noting that for the sea-ice extent trends considered in the previous sections, inter-realization spreads were not much smaller than the inter-model spread, even for multi-decadal trends (see Supplementary Information). For the multi-decadal means of sea-ice extent considered here, inter-realization spread is however much smaller than inter-model spread. Nonetheless, within any single model, internal climate variability can play a significant role in determining sea-ice extent on decadal timescales, and it plays an even more important role on shorter timescales.

Conclusions

When accounting for internal climate variability, observed and simulated September Arctic sea-ice extent trends over 1979–2013 are not inconsistent. Internal variability can also either mask or enhance human-induced changes for decades at a time. Thus, pauses in sea-ice loss, such as seen over the past eight years, are not surprising and are fully expected to occur from time to time. Additional single model large ensembles that capture this variability would be valuable for advancing our understanding. Further evaluating the physical processes responsible for decadal variability in sea-ice extent in both observations and simulations will also improve our ability to understand how sea-ice is likely to evolve in the next few years and decades. ❐

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COMMENTARY:

Connecting the Seas of Norden

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The Nordic Seas are highly sensitive to environmental change and have been extensively monitored and studied across a broad range of marine disciplines. For these reasons, the Nordic seas may serve as a pilot area for integrated policy development in response to ongoing climate change.

The northern high-latitude seas and their coastal waters are among the most sensitive to climate change on Earth. Salinity, temperature and oxygen gradients will become steeper, wind patterns will shift, and the rapid increase in atmospheric CO_2 will continue to acidify the ocean. The critical question — not only for scientists across all disciplines, but also for policymakers and society in general — is how the combination of all these stressors will impact the interdependent ecosystems as well as the social systems within this region.

These seas of Norden[1] are defined here as the Norwegian, Barents, Greenland and Iceland seas, as well as the Baltic and the North seas together with the ocean areas connecting them. Recognizing that they are interconnected, not only with each other, but also with human well-being and health, is a critical step in creating a chart to navigate science and policy towards a common goal of sustainability. Collaboration across scientific disciplines, between science,

Correction

In the Commentary 'Influence of internal variability on Arctic sea-ice trends' (*Nature Clim. Change* **5,** 86–89; 2015), in Fig. 3c, the *x*-axis label for pause length of 20 years was incorrectly repeated. Corrected after print 16 April 2015.