Observations reveal external driver for Arctic sea-ice retreat

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[1] The very low summer extent of Arctic sea ice that has been observed in recent years is often casually interpreted as an early-warning sign of anthropogenic global warming. For examining the validity of this claim, previously IPCC model simulations have been used. Here, we focus on the available observational record to examine if this record allows us to identify either internal variability, self-acceleration, or a specific external forcing as the main driver for the observed sea-ice retreat. We find that the available observations are sufficient to virtually exclude internal variability and self-acceleration as an explanation for the observed long-term trend, clustering, and magnitude of recent sea-ice minima. Instead, the recent retreat is well described by the superposition of an externally forced linear trend and internal variability. For the externally forced trend, we find a physically plausible strong correlation only with increasing atmospheric CO_2 concentration. Our results hence show that the observed evolution of Arctic sea-ice extent is consistent with the claim that virtually certainly the impact of an anthropogenic climate change is observable in Arctic sea ice already today. **Citation:** Notz, D., and J. Marotzke (2012), Observations reveal external driver for Arctic sea-ice retreat, *Geophys. Res. Lett.*, *39*, L08502, doi:10.1029/2012GL051094.

1. Introduction

[2] Arctic sea ice is currently retreating rapidly (Figure 1) [cf. *Fetterer et al.*, 2002, 2010; *Meier et al.*, 2007]. Such a change in the sea-ice cover is a more general indicator for climatic changes than are temperature trends alone, because sea-ice extent depends on integrated changes over several years of many different climate variables such as wind patterns, temperature, and oceanic heat transport. Hence, being able to attribute the observed retreat to either internal variability of the climate system, self amplification or a specific external forcing is of both scientific and societal importance for the general discussion of anthropogenic global warming.

[3] Based on climate-model simulations, a number of previous studies have found that the observed retreat is at least in part caused by anthropogenic emissions of greenhouse gases [*Vinnikov et al.*, 1999; *Gregory et al.*, 2002; *Min et al.*, 2008]. In contrast to such earlier studies, we here focus on the observational record to attribute the observed sea-ice evolution to any of the possible drivers: By examining with which possible driver the observed sea-ice retreat is most compatible, we are able to identify the most likely main driver of the observed retreat without having to focus on climate-model simulations.

[4] In an earlier study that examined the observational record of sea-ice extent, *Meier et al.* [2007] concluded that the downward trend during the satellite area is significant. Here, we move beyond this work by more quantitatively examining the differences between a pre-satellite and a satellite record of sea-ice extent, which allows us to identify specific drivers of the observed retreat. To do so, we proceed as follows: first, we present the data sources in section 2. Then, in section 3,we examine if the sea-ice evolution in recent years is compatible with internal variability. In section 4, we examine if self-acceleration plays a major role in Arctic sea-ice retreat. Finally, in section 5, we examine if external drivers have contributed to the observed retreat.

2. Data Sources

[5] To estimate the internal variability of Arctic sea-ice extent for modern conditions, we use sea-ice data from reconnaissance flights and ship observations that are collected in the HadISST dataset [*Rayner et al.*, 2003; *Met Office Hadley Centre*, 2006]. While this record provides sea-ice data from 1880 onwards, we here focus on the period 1953–1978 (“pre-satellite record” in Figure 1). We chose this reference period for the following reasons (see auxiliary material for details).[1]

[6] First, the data within the HadISST record that predate 1953 are considered less reliable than those from 1953 onward [*Meier et al.*, 2007].

[7] Second, from 1979 onwards the HadISST data set is primarily based on satellite observations. We find across the 1978/1979 boundary an unusually large increase in sea-ice extent in March and an unusually large decrease in sea-ice extent in September (Figures 1b and 1d). This indicates a possible inconsistency in the data set across this boundary.

[8] Third, since there is no significant trend in sea-ice extent during the period 1953–1978 in the HadISST data, we can compare this time period with model simulations of internal variability. Doing so, we find good agreement between the internal variability of sea-ice extent as simulated by a 500-year long model simulation of the Max-Planck-Institutes’ Earth System Model ECHAM5/MPIOM (see Figure 2a and auxiliary material for details).

[9] Fourth, considering the entire HadISST record from 1880 until 1978, the lowest sea ice extent for all months but June fall within the period 1953–1978. Hence, the sea-ice state during that time is closer to the sea-ice extent during the satellite record than the earlier data within the HadISST record, which minimizes a possibly distorting impact of land-mass distribution on our analysis [cf. *Eisenman*, 2010].

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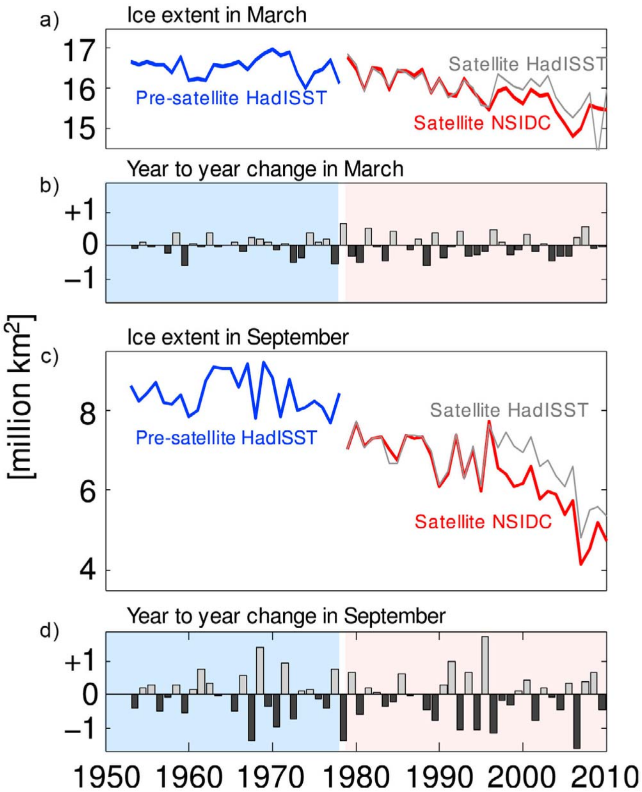

Figure 1. Evolution of Arctic sea-ice extent in (a) March and (c) September and the year-to-year changes in (b) March and (d) September. For this figure, an offset of $+0.35 \cdot 10^6$ km^2 in September and of $-0.16 \cdot 10^6$ km^2 in March has been added to the entire original NSIDC dataset [*Fetterer et al.*, 2002, 2010] to make the time series consistent with the original HadISST satellite time series during the period 1979–1996 [*Met Office Hadley Centre*, 2006].

[10] Some uncertainty nevertheless remains in our estimate of internal variability from the rather short pre-satellite record during the period 1953–1978. Therefore, we employ a number of additional measures to ensure that we are very conservative in possibly rejecting the null hypothesis that internal variability as displayed by the pre-satellite record can explain the sea-ice evolution from 1979 until 2010. For this latter period, we use satellite observations collected in the NSIDC Sea Ice Index [*Fetterer et al.*, 2002, 2010] ("satellite NSIDC record" in Figure 1). We use the NSIDC record rather than the HadISST record from 1979 onwards because the NSIDC record provides a more consistent interpretation of the satellite period [*Meier et al.*, 2007].

3. Internal Variability

[11] In order to minimize the impact of the change in operational technique that possibly affected the absolute values of sea-ice extent across the 1978/1979 boundary, we independently remove the mean annual cycle from each of our two data sets to obtain two time series of monthly deviations from the long-term mean. This results in a very conservative estimate of the recent sea-ice reduction relative to the long-term mean, since the mean annual sea ice extent that we remove from the pre-satellite record ($13.3 \cdot 10^6$ km^2) is much larger than the one that we remove from the satellite record ($11.8 \cdot 10^6$ km^2). We conservatively include all data until December 2010 into the estimate of the long-term mean during the satellite period, in line with our null hypotheses that any event during that time is caused by internal variability.

[12] Because we find very close agreement of the statistical properties of the pre-satellite record with both the linearly-detrended satellite record (see section 5) and with the model simulations of internal variability, we assume that the properties of the pre-satellite record are a good estimate of internal variability. For example, the standard deviation of the pre-satellite record is $\sigma_{presat} = 0.36 \cdot 10^6$ km^2, whereas $\sigma_{sat,\ detrended} = 0.35 \cdot 10^6$ km^2 and $\sigma_{model} = 0.37 \cdot 10^6$ km^2.

[13] In quantifying internal variability from the pre-satellite record, we must take great care to realistically represent the memory of that time series, which carries information over from one month to the next [e.g., *Blanchard-Wrigglesworth et al.*, 2011]. An unsuitable representation of such memory can easily lead to errors of many orders of magnitude in the estimate of statistical significance [*Cohn and Lins*, 2005]. Unfortunately, because of the short length of the satellite series, it is virtually impossible to reliably estimate the most suitable model for its statistical representation [*Maraun et al.*, 2004]. We therefore compare three different representations by approximating the pre-satellite record as either (a) a normal distribution with zero memory, (b) an auto-regressive process (i.e., a process with short memory) or (c) a long-memory process. For each of

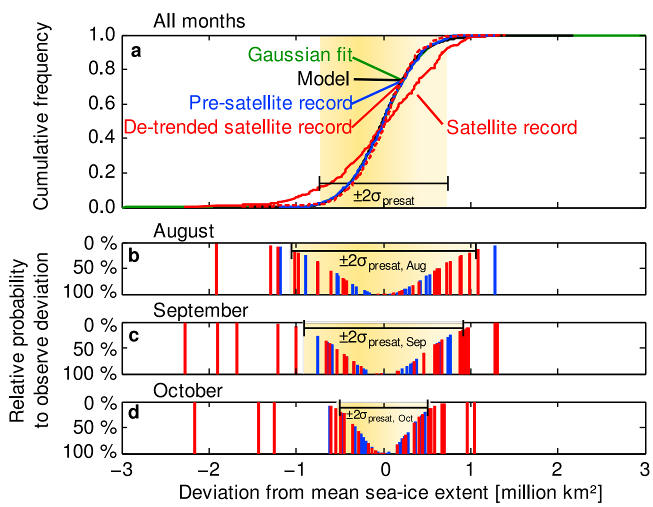

Figure 2. Comparison of the variability of Arctic sea-ice extent. (a) Cumulative frequency of the deviations from the long-term mean as estimated from the pre-satellite record (blue), the model simulation (black), a Gaussian fit to the pre-satellite record(green), the not-detrended satellite record (red solid), and the linearly detrended satellite record (red dashed). (b–d) Deviations from the long term mean of the pre-satellite (red) and satellite (blue) sea-ice extent during August, September and October. The length of the lines is given by one minus the likelihood of observing such deviation. The shaded areas denote plus/minus two standard deviations for that month from the pre-satellite record. Note that in Figures 2b–2d many lines of the pre-satellite record are hidden behind those of the satellite record within the yellow-shaded area.

Table 1. Summary of Monte-Carlo Simulation for a Normal-Distributed Zero-Memory Process, for an Auto-regressive Process of Order 1 (AR(1)), and for Long-Term Memory Processes With Different Hurst Coefficients ($H = 0.8$ and $H = 0.9$)[a]

	Normal Distribution $\sigma_{\mathbf{presat}} = 0.36$	AR(1) $\alpha_{\mathbf{presat}} = 0.71$	Long-Memory $H = 0.8$	Long-Memory $H = 0.9$
2005 minimum ($5.6 \cdot 10^6$ km^2)	62%	56%	60%	54%
2007 minimum ($4.3 \cdot 10^6$ km^2)	$5 \cdot 10^{-8}$	$2 \cdot 10^{-7}$	$<10^{-7}$	10^{-7}
2008 minimum ($4.7 \cdot 10^6$ km^2)	$3 \cdot 10^{-5}$	$3 \cdot 10^{-5}$	$3 \cdot 10^{-5}$	$3 \cdot 10^{-5}$
2009 minimum ($5.4 \cdot 10^6$ km^2)	13%	13%	11%	12%
2010 minimum ($4.9 \cdot 10^6$ km^2)	$6 \cdot 10^{-4}$	$7 \cdot 10^{-4}$	$6 \cdot 10^{-4}$	$6 \cdot 10^{-4}$
Largest N	31	97	91	140
$N_{0.1\%}$	17	47	45	70
Chance to observe $N = 100$	10^{-28}	10^{-8}	10^{-8}	10^{-5}

[a]First to fifth rows: likelihood to observe a certain minimum in September sea-ice extent. Sixth row: longest series of N consecutive months below long-term mean. Seventh row: maximum number of consecutive months below the long term mean that is found in at least 0.1% of all time series. Eighth row: chances to observe 100 or more consecutive months below the long term mean ($N = 112$ for satellite record, with all months below long-term mean since September 2001).

these representations we have carried out a Monte-Carlo simulation [*Zorita et al.*, 2008] to examine the distribution of extreme sea-ice minima from a large number (somewhat arbitrarily chosen as 10^7) of synthetic time series of the length of the satellite record.

[14] Assuming short memory of the sea-ice extent record, we find that the monthly anomalies of the pre-satellite record can be approximated by an auto-regressive process of order one (AR(1)), with an autoregressive coefficient α_{presat} = 0.71 and a noise covariance of $\sigma^2_{Z,\ presat} = 0.66 \cdot 10^6$ km^2.

[15] For the long-term memory process, we estimate the Hurst coefficient H of the pre-satellite time series using detrended fluctuation analysis (DFA) [*Peng et al.*, 1994]. Only a rough estimate of $0.8 < H < 0.9$ is possible both because of the short length of the time series and because DFA shows non-stationarity even after removal of the seasonal cycle. The obtained range of H is in good agreement with the values found for much longer time series of atmospheric temperature above the ocean [*Fraedrich and Blender*, 2003]. This can be expected since sea-ice extent is to a significant part driven by fluctuations in atmospheric temperature.

[16] The results from our Monte-Carlo simulation are summarized in Table 1. For all three statistical models, we find that any one of the sea-ice minima of 2005, 2006 and 2009 can be explained by internal variability if one includes the extreme minima from 2007 onwards in the calculation of the time series' mean. The sea-ice minima of 2007, 2008 and 2010 are, however, so low that chances are extremely small that any one of them was caused by internal variability (Table 1, first to fifth rows; Figures 2b–2d). It is not surprising that chances to observe a specific, individual extreme minimum do not increase with the inclusion of a certain memory, since any realistic representation of the original time series must necessarily match the overall internal variability of that original time series.

[17] In contrast, there is a very large impact of the time series' memory on the clustering of extreme events. We here quantify the clustering of extreme sea-ice minima by using the number N of consecutive months with below-average sea-ice extent. For the observational record, $N = 112$ since all 112 months between September 2001 and December 2010 were below the long-term mean. For our synthetic time series, the distribution of N decays exponentially with increasing N (Figure 3), and we can extrapolate the likelihood to observe $N > 100$ for any of our statistical models (Table 1, eighth row). Doing so, we find for AR(1) a likelihood of 10^{-8} for $N \geq 100$. Roughly the same value is found for the long-term memory time series with $H = 0.8$. For the long-memory time series with $H = 0.9$ we find that chances to observe $N \geq 100$ are about 10^{-5} – somewhat larger than for the short-memory process but still extremely small. Assuming that the observations of sea-ice extent are independent and normally distributed, we find a likelihood of 10^{-28} for $N \geq 100$, more than 20 orders of magnitude smaller than the result for the long-memory time series.

[18] Focussing finally on the observed trend of the satellite record, we again find that this trend can not be explained by internal variability, independent of the underlying statistical model. As shown by *Meier et al.* [2007], this trend is highly significant at the 5 % level if one assumes that the time series displays short-term memory. We find the same for our synthetic time series, with none of the short-term memory time series showing a more significant trend than the satellite record. Of the 10^7 time series with long-term memory, a more significant trend is displayed for $H = 0.9$ by only 420 time-series (i.e., 0.004 %) and for $H = 0.8$ by only 12 timeseries (i.e., 10^{-4} %).

[19] Hence, we find that independent of the underlying memory of the time series, internal variability is extremely

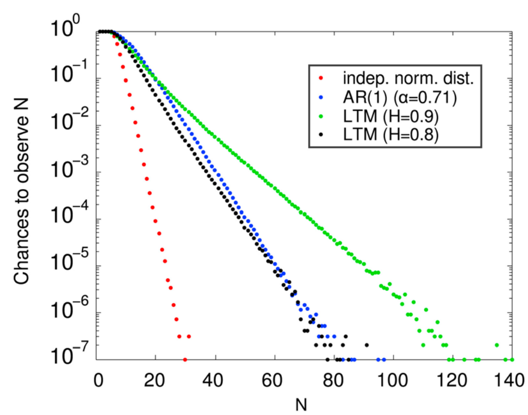

Figure 3. Likelihood to observe a certain number N of consecutive months below the long-term mean in a time series as long as the satellite record for a time series with no memory (red), short-term memory (blue), long-term memory (green and black).

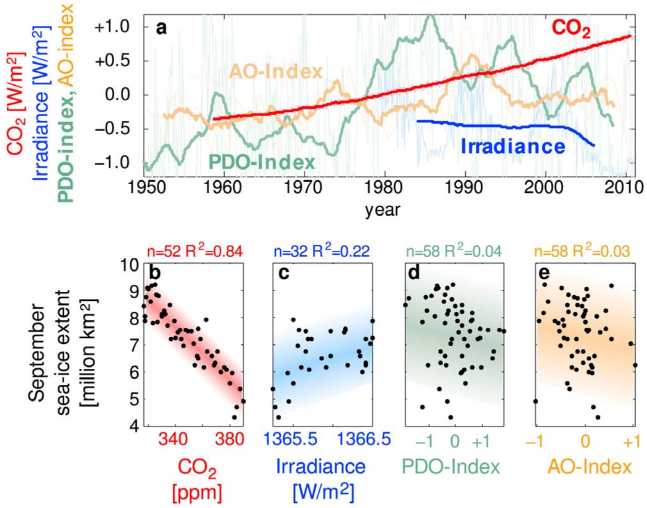

Figure 4. Relationship between sea-ice evolution and various forcings. (a) Temporal evolution of solar irradiance [*Fröhlich*, 2000], AO-index [*Thompson and Wallace*, 1998], PDO-index [*Mantua and Hare*, 2002], and CO_2 concentration (scaling with a 1.66 W/m^2 equivalence for a 100 ppm increase [*Intergovernmental Panel on Climate Change*, 2007]). The thin lines denote monthly values, while thick lines denote averages over 1 year (CO_2), 5 years (AO-index, PDO-index) and 10 years (solar irradiance). (b–e) September sea ice extent from 1953 until 2010 is plotted against annual mean values of the various forcings whenever data was available. The R^2 values are calculated for a standard linear regression as indicated by the shading ($\pm 2\sigma$).

unlikely to explain the recent trend, clustering, and magnitude of the observed Arctic sea-ice retreat.

4. Self-Acceleration

[20] We now turn to the question if self-acceleration could possibly be responsible for the observed retreat. Such self-acceleration has been suggested in the context of the so-called ice–albedo feedback: Since dark water absorbs more sun light than bright sea ice, any retreat of sea ice leads to additional heating of the Arctic Ocean, which in turn could lead to further and hence self-accelerating loss of sea ice.

[21] However, the observational record is incompatible with self-acceleration dominating the observed sea-ice evolution. In the time series of year-to-year changes (Figure 1), every strong negative year-to-year change in sea-ice extent is followed by a positive year-to-year change and vice versa. Analyzing this behaviour in more detail, we find a significant negative 1-year lag auto-correlation throughout summer for the year-to-year changes of both the satellite and the pre-satellite record (see auxiliary material). This shows that the ice-albedo feedback that could lead to self-acceleration of sea-ice retreat or advance must currently be more than compensated for by negative feedbacks that prevent such self-acceleration and a possible "tipping point" (consistent with other recent studies [*Eisenman and Wettlaufer*, 2009; *Notz*, 2009; *Tietsche et al.*, 2011]).

[22] The fact that the sea-ice retreat is apparently not strongly self-accelerating might explain why we find an extremely small likelihood that it can be caused by internal variability: In the past, sea-ice extent always recovered after an extreme minimum, which prevented under pre-industrial climate conditions the occurrence of very low minima such as those observed in 2007 and 2008. Note that we here only deal with sea-ice extent. Model reconstructions of sea-ice volume show a more persistent downward trend [*Schweiger et al.*, 2011], which in turn increases chances of extreme minima in sea-ice extent [*Notz*, 2009].

5. External Forcing

[23] Since internal variability and self-acceleration cannot explain the observed sea-ice retreat, we finally examine the relationship between the observed retreat and external forcings. For such an analysis it is instructive to split the satellite record up into two components: a component that is based on the significant negative trend that we have described in section 3, and a component caused by internal variability [cf. *Serreze et al.*, 2007]. Splitting up the satellite record accordingly gives a standard deviation $\sigma_{sat,\ detrend} = 0.35 \cdot 10^6$ km^2, virtually identical to the value of the pre-satellite record $\sigma_{presat} = 0.36 \cdot 10^6$ km^2 (see also Figure 2a). Also the seasonal distribution of this variability is similar between these two records.

[24] This agreement strongly suggests that the satellite record can be described by internal variability of roughly the same magnitude as the pre-satellite record, plus an additional linear, negative trend that is caused by some external forcing. The linearity of this trend is consistent with the assumption that sea-ice retreat is not self-accelerating.

[25] Looking for the most likely external driver for this linear trend, a simple correlation analysis is useful. Based on our physical understanding of the climate system, we expect a decreasing sea-ice extent to be caused for example by increasing solar irradiance, by increasing greenhouse gas concentrations, and by high indices of the Arctic Oscillation (AO) [*Rigor et al.*, 2002] and/or the Pacific Decadal Oscillation (PDO) [*Lindsay and Zhang*, 2005], which describe long-term internal variability of prevailing weather patterns.

[26] Searching for physically consistent correlations of sea-ice extent with any of these external drivers, we find a very weak relationship with solar forcing (Figure 4c) the direction of which is unphysical: an increase in irradiance is found to coincide with an increase in sea-ice extent. This unphysical correlation allows us to exclude solar irradiance as the main driver of Arctic sea ice evolution in recent decades.

[27] The indices of the Pacific Decadal Oscillation (PDO) (Figure 4d) and of the Arctic Oscillation (AO) (Figure 4e) show only a very weak direct impact on the observed sea-ice retreat. These factors contribute of course to the evolution of sea-ice extent, but the weak long-term relationship is indicative of their only secondary importance for the long-term evolution of sea-ice extent. We also examined a possible correlation of these indices with year-to-year changes but found no significant correlation, either.

[28] However, we do find a significant correlation between decreasing sea-ice extent and the increasing CO_2 concentration, with $R^2 = 0.84$ (Figure 4b) [see also *Johannessen*, 2008]. Given that both time series display a trend, the magnitude of this correlation must of course be interpreted carefully. A direct relationship between CO_2 concentration and sea-ice extent can be expected, since the incoming long-wave

radiation dominates the annual mean surface heat balance of sea ice in the Arctic [e.g., *Maykut and Untersteiner*, 1971]. If this radiation is increased because of increasing CO_2 concentrations, a decreasing sea-ice extent would be a direct consequence.

[29] The fact that we (a) have strong physical arguments for a possible causal relationship between CO_2 and Arctic sea-ice extent, and that we (b) find a pronounced correlation between the two in the observational record is very suggestive of a causal relationship between the observed increase in atmospheric CO_2 concentration and the decreasing Arctic sea-ice extent. We are not aware of a similarly large and physically plausible correlation between sea-ice extent and any other external driver. Such correlation would require a strong trend in the external driver consistent with the observed sea-ice decrease. However, a strong trend is not found in the other external drivers discussed before, nor has it been observed, for example, in cosmic rays [*Chowdhury et al.*, 2010], volcanic eruptions [*Ammann et al.*, 2003], or poleward oceanic heat transport [*Schauer and Beszczynska-Möller*, 2009].

[30] Hence, unless there is some external driver with a strong trend that we have not considered, we can conclude that the most likely explanation of the downward linear trend in sea-ice extent is the increase in atmospheric CO_2 concentration.

[31] Note that the same reasoning allows us to conclude that changes in CO_2 concentration are not the main driver for the observed sea-ice evolution in the Antarctic. With no clear trend in the sea-ice extent there, there is virtually no correlation with the increasing CO_2 concentration. This underpins the fact that in the Antarctic, sea-ice extent is at the moment primarily governed by sea-ice dynamics. In contrast, in the Arctic the sea-ice movement is constrained by the surrounding land masses and the thermodynamic forcing becomes more relevant there.

6. Conclusions

[32] In this contribution, we have shown that the following conclusions can be drawn from an analysis of the available observational record:

[33] 1. Internal variability as estimated from pre-satellite observations cannot explain the recent retreat of Arctic sea ice.

[34] 2. The observational record shows no signs of self-acceleration and hence no signs of a possible ‘tipping’.

[35] 3. The satellite record is well described by a linear trend onto which internal variability is superimposed. The magnitude of this superimposed internal variability is very similar to that of the pre-satellite record.

[36] 4. The most likely explanation for the linear trend during the satellite era from 1979 onwards is the almost linear increase in CO_2 concentration during that period.

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