Fluctuations and seasonality in the Arctic sea ice area: A sudden regime shift in 2007?

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ABSTRACT
Since the beginning of satellite observations, the Arctic sea ice extent has shown a downward trend. The decline has been weaker in the March maximum than in the September minimum and masked by inter-annual fluctuations. One of the less understood aspects of the sea ice response is the persistence times for fluctuations, which could indicate the dominant physical processes behind the sea ice decline. To determine the fluctuation persistence times, however, it is necessary to first filter out the dominant effect of the seasonal cycle. In the current study, we thus develop a statistical model, which accurately decomposes the ice area changes into: (1) a variable seasonal cycle component with a constant shape and (2) a residual (short term) fluctuation.

We find the persistence time of fluctuations to be only about three weeks, independently from season, which is substantially shorter than previously reported. Such short time scale points to the dominance of atmospheric forcing. The shape of the seasonal cycle is surprisingly constant for the whole observational record despite the rapid decline. This is in agreement with the suggestion that the asymmetry of the seasonal cycle is an effect of Arctic land-sea geography, which has not changed with climate change.

The analysis suggest a jump in the annual sea ice area amplitude occurring in 2007, from which it has not yet recovered, possibly revealing a permanent amplitude shift. In physical sense, this could imply a shift towards the younger, thinner and more susceptible ice cover commencing after the immense 2007 multi-year ice loss.

1. Introduction
Current observations (Cavalieri and Parkinson 2012) show more dramatic decline in the ice area than predicted by most climate model simulations, despite the major improvements in CMIP5 generation of models (Stroeve et al. 2012; Wang and Overland 2013). Most dramatic is the decrease in the September minimum sea ice area (Stroeve et al. 2012; Cavalieri and Parkinson 2012) with the three lowest ever recorded ice extents occurring in September of 2012, 2007 and 2011, respectively (NSDIC 2012). Ice free summers in Arctic are expected within a few decades (Stroeve et al. 2007; Wang and Overland 2003 2012).

Locally, expected future decline in the Arctic sea ice area will eminently cause huge ecological and socio-economical disturbances such as ecosystem and biodiversity losses, shifts in traditional lifestyles and culture and the pollution of pristine areas, while providing the opportunities for increased trade, shipping and exploitation of natural resources (Arctic Climate Impact Assessment (ACIA) 2004; Monitoring and Assessment Programme (AMAP)). However, remote effects are also anticipated. A number of modeling and observational studies suggest a link between the Arctic sea ice extent and the midlatitude circulation and extreme weather events (Petoukhov and Semenov 2010; Deser et al. 2010; Francis and Vavrus 2012; Liu et al. 2012; Bithsen et al. 2012) while paleo-studies imply possible remote effects in terms of tropical precipitation shifts (Chiang and Bitz 2005; Broccoli et al. 2006; Cvijanovic and Chiang 2013).

The sea ice extent is influenced by a number of atmospheric and oceanic processes with some of the key factors being surface air temperature and radiative flux changes, ocean state, interactions with cloud cover as well as the ocean current and atmospheric circulation changes that facilitate the sea ice export out of the Arctic (Dickson et al. 2000; Serreze et al. 2007; Kay and Gettelman 2009; Proshutinsky et al. 2009; Ogi and Wallace 2012). Atmospheric patterns such as North Atlantic Oscillation (NAO) and the Northern Annular Mode (NAM) are believed to be closely linked to sea ice changes (Rigor and Wallace 2004; Rothrock and Zhang 2015). The large natural variability and the limitations in understanding the effect of climate change on patterns like the North Atlantic Oscillation (NAO) and the Northern Annular Mode (NAM) (Dickson et al. 2000; Rigor et al.)
make projections difficult.

An important indicator of physical processes determining the sea ice area is the correlation time for fluctuations \cite{Blanchard-Wrigglesworth2011}. However, for a signal with a strong deterministic variation, in this case the seasonal cycle, the true statistical correlation can be masked. This can be illustrated on the example of sinusoidal seasonal signal (with added noise), where the autocorrelation will simply reproduce the sinusoidal shape, giving an artificial positive correlation with a lag of 1 year that is unrelated to the residual statistical fluctuations. In order to investigate this part of the signal, which in the following will be denoted the short term fluctuation, the seasonal cycle must be removed. This is not a trivial task, since the seasonal cycle itself is subject to changes. Thus, in order to better understand how the Arctic sea ice responds to climate change, observed variations are analyzed using a new decomposition of the seasonality in the total ice area.

It is found that the shape of the seasonal cycle is stable, even though the annual mean and the amplitude change substantially. This is in agreement with the recent suggestion that the geography of the Arctic basin, which is constant, mutes the winter sea ice area \cite{Eisenman2010}. Temporal analysis of the seasonal amplitude cycle shows a jump to higher amplitude in 2007 that has not been followed by a recovery, indicating a likely shift in the amplitude of the seasonal cycle.

The paper is organized as follows: Satellite data used to obtain the sea ice area is described in Section 2, followed by the description of the statistical method used for the decomposition of the annual cycle (Section 3). Derived time scale for short term fluctuations as well as the change in the annual mean sea ice area and amplitude are discussed in Section 4. Summary and considerations on possible physical interpretations are given in Section 5.

\section{The data}

The sea ice area is derived from NASAs Satellite-based Scanning Multichannel Microwave Radiometer \cite{Cavalieri1996} for the period 1979-present: 1979-1987, SMMR from the NASA Nimbus-7 satellite, 1987-present SSM/I on U.S. Defense Meteorological Satellite Program (DMSP) platforms, with the most recent data (from 2008) using the next-generation SSMIS sensor, replacing SSM/I. For further information see National Snow and Ice Data Center’s webpage: \url{http://nsidc.org/data/}. The data record analyzed is obtained from the University of Illinois’ cryosphere project webpage \cite{TheCryosphereToday}. The observed record (figure 2, top panel), covers the Arctic Ocean and surrounding waters in the period 1979-present with daily resolution (every second day prior to 1987). In this analysis the ice area, defined as the area weighted by concentration is used. The ice extent, defined as the area covered by 15% or more ice is another reported measure. The ice area is arguably a more relevant climatic variable, while the ice extent data is probably of better quality. Thus the following analysis has been repeated using the ice extent (see Supplement: \url{www.gfy.ku.dk/~pditlev/seeice-suppl.pdf}) with results almost identical to the ones presented for the ice area.

Seasonal variations of the Arctic sea ice area since the start of the satellite measurements (1979) are shown in figure 1 (a). A year round decline is seen after 2007 with a remarkable decrease in annual mean (red and green curves).

In order to quantify the change in the seasonal cycle of the sea ice area, denoted \(x_i(t)\), we decompose it as

\[ x_i(t) = m_i + A_i f(t) + \epsilon_i(t), \]

where \(i \in (1979, 2011)\) denotes year, and \(t \in (1, 365)\) denotes day of year. The mean \(m_i\) and amplitude \(A_i\) are constant within a given year \(i\). The function \(f(t)\) is defined to have zero mean and unit variance. It represents the (constant) seasonal cycle. The residual fluctuation \(\epsilon_i(t)\) is assumed in a statistical sense to be a simple stochastic noise. We will refer to \(\epsilon_i(t)\) as the short term fluctuation.

It is not given a priory that this is an adequate description of the Arctic sea ice area. However, by plotting the normalized ice area \((x_i(t) - m_i)/A_i = f(t) - \epsilon_i(t)/A_i\), we see an almost perfect collapse of the data (figure 1(b)). Details on how \(m_i\) and \(A_i\) are calculated are given in the appendix.

The function \(f(t)\) can be accurately estimated as the mean of the normalized ice area for all years (figure 1(c)). As the difference between the two lower panels in figure 1 is small, the short term fluctuation \(\epsilon_i(t)\) is small. This short term fluctuation is plotted in blue in figure 2(b), (note the scale in comparison to the scale in figure 2(a)).

Two findings are surprising regarding the derived fluctuation \(\epsilon(t)\): Firstly, despite the dramatic reduction in Arctic sea ice through the record, there are no trends. Secondly, the short term fluctuation is in a statistical sense indistinguishable from a red noise with a correlation time of \(\tau = 22\) days. This is seen from the autocorrelation being exponential (figure 2(c)) and the compensated signal

\[ \tilde{\epsilon}(t) = \epsilon(t) - \exp(-1/\tau)\epsilon(t+1) \]

is perfectly uncorrelated and structureless (figure 2(d)).

In order to additionally confirm that there is no seasonal dependence, the short term fluctuation it is plotted as a function of time of the year for the 33 year record in figure 3(a). The color coding is as in figure 1, showing no difference between the recent period (2007-2011 in red) and the previous period (1979-2006 in blue). Furthermore, following \cite{Blanchard-Wrigglesworth2011}, the correlation times calculated from the first day of each month (not shown), also reveals no seasonality in the persistence time for the sea ice.

The advantage in considering the short term fluctuation compared to the annual anomaly can be understood when
comparing figure 3 (a) and figure 3 (b), where the latter shows the annual anomaly (green curve in figure 2(b)). A clear shift between the early and the late part of the record is seen in figure 3 (b) with a pronounced seasonal cycle retained in the late part of the record. This is a consequence of the mean and amplitude of the annual cycle changing with time. As a further consequence the correlation time in the anomaly record will be on the order of a season.

The finding of a 22 days correlation time for fluctuations is in contrast to previous findings of persistence time of several months varying with season. Their result is likely a consequence of the persistence in the annual cycle, that is largest at the extremes and smallest at spring and fall, when melting and refreezing results in fast changes in the ice cover. The influence of the annual cycle on the autocorrelation of the sea ice is also noted in Agarwal et al. 2012.

The correlation time is consistent with the time scale of variations in sea ice area governed by the natural atmospheric variability, while it is short in comparison to the typical persistence times for SST anomalies.

The annual cycle function \( f(t) \) is almost identical to the usual annual mean \( \langle x_i(t) \rangle \), normalized to zero mean and unit variance. Here \( x_i(t) \) denotes average for day \( t \) in the year over all the years. But the short term fluctuation \( \epsilon_i(t) \) is very different from the usual anomaly \( x_i(t) - \langle x_i(t) \rangle \). Livina and Lenton 2012, Ditlevsen 2012, which is plotted in green in figure 2(b). The anomaly cannot be considered as a stationary independent noise.

The sea ice area at any particular day of the year is easily obtained from the decomposition, thus we have the summer minimum \( \min_i = m_i - 1.62 A_i \), where \( \min(f(t)) = f(September \ 8) = -1.62 \) and the winter maximum \( \max_i = m_i + 1.27 A_i \), \( \max(f(t)) = f(March \ 9) = 1.27 \). These are shown in figure 2(e), both with downward trends, most pronounced in the summer minimum. Note that the natural variability unrelated to climate change, represented by \( \epsilon_i(t) \) is filtered out of the estimates for \( \min_i \) and \( \max_i \).

The annual mean \( \bar{m}_i \) (figure 4(a)), shows, as has been reported before Stroeve et al. 2012, Lindsay et al. 2009, Comiso et al. 2008, Maslanik et al. 2007, a downward trend through the full record, while the amplitude of the seasonal cycle \( A_i \) (figure 4(b)) has a distinct minimum for 1996 and a sudden positive jump in 2007, not followed by a recovery, thus possibly indicating a new state. This could be a consequence of the shift towards the one-year ice Maslanik et al. 2007 and will be further discussed in Section 4.

3. Results: The annual mean and the amplitude

The linear trend in the mean ice area \( m_i \) is shown in figure 4(a). No significant changes in the linear trend can be detected, though an increased downward trend with low statistical significance has been suggested Comiso et al. 2008. There is no significant trend in the amplitude of the seasonal cycle either over the period 1979-2006 (figure 4(b)). However, in 2007 there is a jump to a higher level, which has not been followed by a recovery up to this time. The blue lines in figure 4(b) show the means for the periods 1979-2006 and 2008-2011, while the green dashed line shows the mean for the full record. Denoting the detrended mean by \( \tilde{m}_i \), the joined distribution of \((A_i, \tilde{m}_i)\) is shown in the scatter plot in figure 4(c), where the color coding for five points is the same as in figure 1(a). Here a change in joined statistics is observed in 2007. The ellipses show the 90% and 98% contour lines for the maximum likelihood bivariate normal distributions for the two populations 1979-2006 (blue points, and the 1996 outlier (in black)) and 2007-2011 (red points). Obviously, the estimate of the distribution after 2007 is uncertain, since it is based on only five points. The slight tilt in the ellipses around the last five (red) points in figure 4(c) is not significant, thus there is no significant correlation between the detrended mean and the amplitude. The change in amplitude in 2007 is not just a consequence of the summer minimum decreasing more than the winter maximum. Subtracting the trends from the winter maxima and summer minima, the scatter of detrended maxima vs. (minus) the detrended minima is shown in figure 4(d). It is clearly seen that the (detrended) yearly minima and maxima are uncorrelated, and that the last part of the record does not show a significantly different distribution. The same is the case for the summer minimum and the winter maximum of the following year (not shown). Thus the change point in 2007 showing up in the amplitude is masked by the overall trend in summer minimum and winter maximum.

4. Discussion and Summary

In summary, the decomposition (1) of the seasonally varying Arctic sea ice area gives a much clearer insight into the variations than the traditional decomposition into the mean annual cycle and the anomaly, most strongly expressed in the difference between the short term fluctuation and the anomaly in figure 2(b). The correlation time for the fluctuation, that is independent from the annual cycle, is 22 days which points to atmospheric variability as driver, while the ocean state changes and other forcing are reflected in the mean and amplitude of the annual cycle.

The mean \( m_i \) shows a steady decline, while the amplitude \( A_i \) shows a sudden jump in 2007 as shown in figure 4 (a) and (b). The amplitude and the detrended noise \((A_i, \tilde{m}_i)\) is independent from year to year following a bivariate normal distribution, with a sudden change in distribution in 2007.

The annual cycle is surprisingly regular, where only the annual amplitude and mean change from year to year. This is remarkable for two unrelated reasons: firstly, the varia-
tions in the total ice area includes regions with large vari-
ations and a negative trend in the mean.

Secondly, different changing factors influencing the ice
growth and retreat have distinct seasonalities (Serreze et al.
2007; Lu and Cai 2009). The regularity of the shape of the
annual cycle could be in support of the resent suggestion
that the geography of the Arctic basin, which is constant,
determines the shape by muting the winter sea ice area
(Eisenman 2010). The decomposition of the sea ice area
(1), and the constancy of the normalized annual cycle, in-
dicate that all these factors add up such that the annual
amplitude is the strongest indicator of climate change.

As there was no recovery in the amplitude of annual sea
ice area after the 2007 jump, we refer to it as a shift into
a new state with the increased amplitude of the seasonal
cycle. According to (Maslanik et al. 2007), summer of
2007 suffered extreme Arctic ice loss with the ice extent 42
percent smaller compared to its value in the mid-eighties.
The 2007 Arctic sea ice loss was unprecedented due to the
fact that it was not the increased transport out of the Ar-
tic that was responsible for this record low (as it was the
case for the record lows prior to 2007). It was the ac-
tual failure of sea ice to survive the Arctic summer making
the vast areas north of Alaska and eastern Siberia ice free
(Stroeve et al. 2008). The atmospheric conditions (per-
sistent anticyclone over the Arctic Ocean during the summer
of 2007) and previous years of transition towards the thin-
ner younger ice have majorly contributed to this record low
(Stroeve et al. 2008; Maslanik et al. 2007). The amplitude
shift found in this study, thus very likely represents the ex-
sact signature of a transition towards the younger, thinner
ice that is more susceptible to global warming.

Finally, the described decomposition used in this study
could also be used for testing the models in reproducing the
described short term fluctuation characteristics as well as
the shifts in the amplitude of the seasonal cycle. Available
daily data briefly tested in this study (output from the
Community Climate System Model, version 3 (CCSM3)
Large Ensemble Experiment) were not able to reproduce
the shifts reported in this study. More comprehensive anal-
ysis will be reported elsewhere.

APPENDIX

Decomposing the sea ice area $x(t)$

By averaging equation (1) over the year we estimate

$$m_i = \langle x_i(t) \rangle / \sigma / \sqrt{\bar{n}},$$

where $\sigma$ is the variance of the short term fluctuation $\epsilon(t)$ and $\bar{n} = 365/22$ is the effective
number of independent points within a year. A pos-
terior the relative intensity of the short term fluctuation
is calculated to $\sigma/m = 0.02$, thus the uncertainty is negli-
gible. Likewise we obtain the amplitude from $\langle x_i(t)^2 \rangle_i = m_i^2 + A_i^2 \langle f(t)^2 \rangle_i + \sigma^2 \Rightarrow A_i = \sqrt{\langle x_i(t)^2 \rangle_i - m_i^2}$, where we
have safely neglected the $\sigma^2$ term, which gives a relative
error of less than 0.004. The mean cycle function is ob-
tained as $f(t) = \langle x_i(t) - m_i \rangle / A_i$, where $\langle \rangle_i$ denotes aver-
ing over the 33 years. The uncertainty is of the order

$$\sigma / \langle A_i \rangle / \sqrt{33} = 0.004,$$

thus also negligible. As a consis-
tency check of equation (1), we obtain $\langle f(t)^2 \rangle_i / \sqrt{\langle f(t)^2 \rangle_i} = 0.0015 \approx 0$. The effect on the analysis of changing the be-
inning date for the year is very small (not shown). This
has been checked by repeating the full analysis beginning
the year in April 1., July 1., October 1. and at winter
maximum and summer minimum.

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**Fig. 1.** The seasonal variation in the Arctic sea ice area. (a) shows all the years obtained from the satellite measurements. A year round decline in is seen after 2007. The year 1996 showed a notably small amplitude in the seasonal cycle. (b) Same data as in (a) but normalized by subtracting annual mean and dividing by the seasonal amplitude (2012 excluded). There is a striking collapse of all years despite the pronounced climate change after 2007. (c) The mean annual cycle function is obtained as the day-by-day average of the 33 normalized curves in (b).
Fig. 2. (a) shows the Arctic sea ice area measured from satellites since 1979. (b) shows the short term fluctuation \( \epsilon_i(t) \) in blue (shifted upwards for visibility) and the anomaly \( x_i(t) - \langle x_i(t) \rangle_i \) in green. The anomaly is not stationary, since it is a mixed signal of both changes in mean and amplitude. (c) shows the autocorrelation of the short term fluctuation, which is almost perfectly exponential. The green line is the curve \( \exp(-t/\tau) \), with \( \tau = 22 \) days. (d) The scatter plot of the compensated signal (see text for explanation) shows that there is no structure, beside the simple exponential autocorrelation in the short term fluctuation. (e) shows the winter maximum and summer minimum (observe shifted axis for comparison). These are obtained from the mean and amplitude as \( \text{min}_i = m_i + A_i \min(f(t)) \) and \( \text{max}_i = m_i + A_i \max(f(t)) \) which occur on September 8. and March 9., respectively.

Fig. 3. The curves in figure 2(b) plotted as function of time of the year. The blue curves are 1979-2006, while the red curves are 2007-2011, as in figure 1. (a) the short term fluctuation for the 33 years shows no seasonality and no statistical difference through the record. This verifies that the seasonality is effectively captured in the first terms in equation (1). (b) the annual anomaly, which shows a difference between the two periods, reflecting the fact that the mean and amplitude of the annual cycle change with time. Especially in the recent period 2007-2011, a seasonal cycle is retained in the anomaly. This will result in an artificial seasonal time scale auto-correlation in the anomaly.
Fig. 4. The change in statistics in 2007. (a) shows the annual mean $m_i$, with a negative linear trend through the whole record. No statistically significant change in the trend is observed. (b) The change in the amplitude in 2007 is much more significant. The last five points are much higher than the mean for the period (green dashed line) indicating a change in mean (blue lines). (c) Scatter plot of the detrended mean $\tilde{m}_i$ vs. $A_i$ where the color coding is the same as in figure 1(a). This indicates that 2007 is a change point to a new statistical state. Note that $A_i$ and $\tilde{m}_i$ are independent within the two populations, prior to 2007 (blue and black points) and after 2007 (red points). The ellipses show the 90% and 98% probability contours for the two maximum likelihood bivariate normal distributions. (d) Shows the scatter of the detrended winter maxima vs. detrended summer minima, these are independent and the period 2007-2011 does not show a significantly different joined distribution in comparison to the earlier part of the record.