Extended summary of the Climate Dialogue on Arctic sea ice

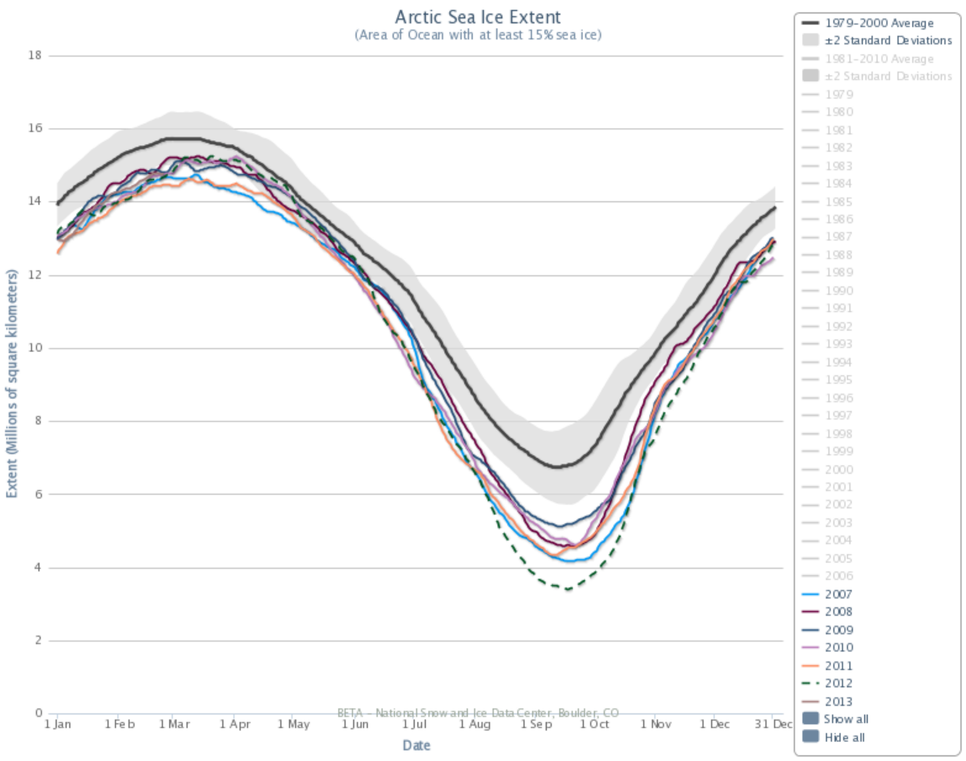
The decline of Arctic sea ice is one of the most striking changes of the Earth's climate in the past three decades. In September 2012 the sea ice extent reached a new record low after an earlier record in 2007. Both ice extent and volume have decreased steadily and if things will continue this way the Arctic will be ice free in the summer some year in the future.

Given the recent new record the melting of the Arctic was the logical choice as the first topic on this new Climate Dialogue platform. We are very glad that Walt Meier, Ron Lindsay and Judith Curry took up the challenge to engage with each other. We also like to thank the many climate scientists and other interested readers who joined the discussion via the public comments. We had over 25,000 hits in the first three weeks, which exceeded our expectation for the first round of discussion.

This summary is solely based on the contributions of the three invited scientists Walt Meier, Ron Lindsay and Judith Curry. It's not meant to be a consensus statement. It's just the summary of the discussion and should give a good overview of how these three scientists view the topic at this moment, i.e. on what they agree and disagree and why. In our introductory article we presented six questions and we will treat each one separately.

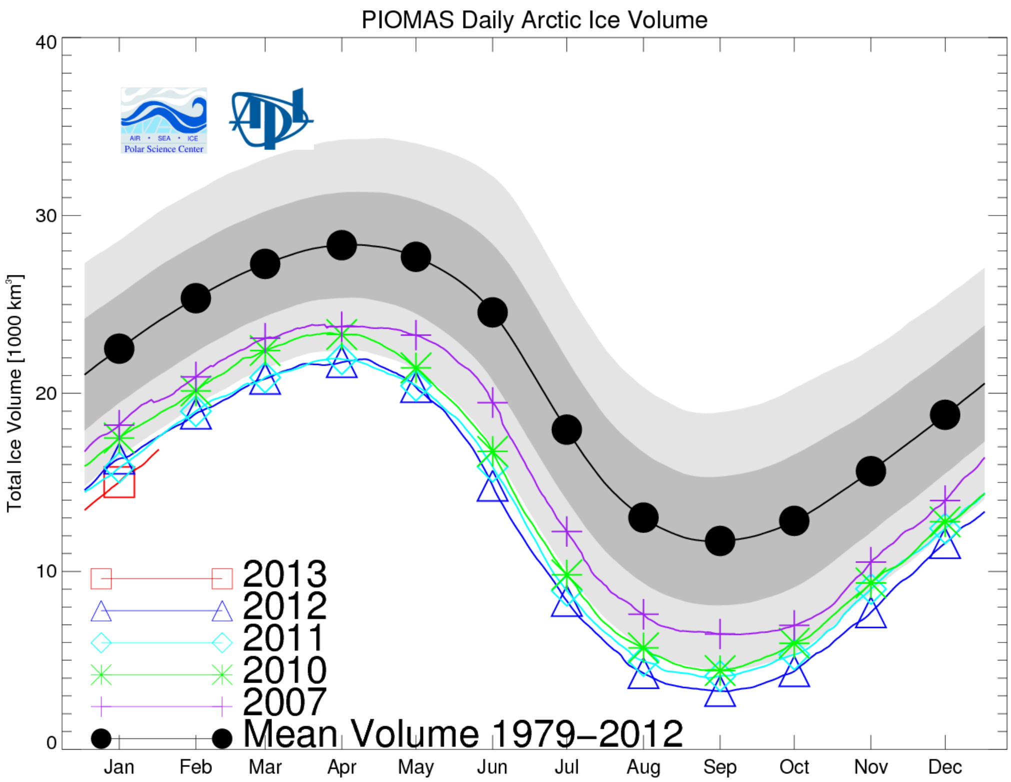
1. What are the main processes causing the decline in Arctic sea ice?

Over the last 30+ years, Arctic sea ice has declined precipitously, particularly during summer. Summer ice extent has decreased by ~50%, including most of the older, thicker ice.



Source: http://nsidc.org/arcticseaicenews/charctic-interactive-sea-ice-graph/

Sea ice volume (as determined by the Piomas model[i]) has decreased even more. The model mean annual cycle of sea ice volume over the period 1979-2011 ranges from 28,700 km3 in April to 12,300 km3 in September. However, monthly averaged ice volume for September 2012 was 3,400 km3. This value is 72% lower than the mean over this period, 80% lower than the maximum in 1979, and 2.0 standard deviations below the 1979-2011 trend.



Source: http://psc.apl.washington.edu/wordpress/research/projects/arctic-sea-ice-volume-anomaly/

There is no disagreement about these facts. However, it is less clear what are the main processes that caused the decline.

The discussants all agree that relatively little heat is necessary to get the melt rates of the recent past. Like Lindsay said: "[…] given the small amount of heat needed to melt the ice at the rate we have seen (less than 0.5 W/m2 annual average), is it a hopeless task to find a definitive mechanism, particularly since the dominant forcing for ice anomalies likely changes from year to year?"

These changes are too small to measure. Lindsay: "It seems this means annual change in the net heat balance of the ice and the changes in the mean annual melt and growth rates are much too small to be accurately measured by any observational system that looks at the entire region." He adds: "[…] teasing out the actual mechanisms for the decline is very tricky (e.g. whether it is changes in the ocean or in the atmosphere or both or what processes are responsible). Observational evidence is difficult to interpret, since the decline itself modifies the lower atmosphere and the surface fluxes. What is cause and what is effect?"

Meier adds that given the small amount of heat necessary to melt the ice it is rather surprising that the sea ice has been relatively stable in the past. "In regards to the stability of the Arctic sea ice, I would agree with Ron [Lindsay] that it may be more surprising that it has been so stable over our years of observations, both in our modern satellite record (since 1979) and earlier. Given that the ice is quite thin (overall on average 2.5 meters or so, with multiyear being 3-4 meters), it doesn't take much forcing, relatively speaking, to melt completely during summer (1 W/m2 or less)."

Ocean

The discussants agree that heat from the ocean is more effective in melting the ice than heat from the air. As Curry puts it: "Melting the ice from below is much more powerful than melting the ice from above, in terms of W/m2. Note that solar radiation penetrates into the mixed layer through open water leads and melt ponds and thin ice, so solar acts to melt from below as well as from above."

Curry also referred to model calculations that tried to figure out how much heat from the atmosphere would be needed. "From the Arbetter et al. paper[ii], which asked how much IR forcing is needed to melt the ice from above, the answer depended on which sea ice model you used, but for a dynamic/thermodynamic sea ice model, the result was tens of W/m2."

Meier: "The ocean is indeed a very important part of the sea ice melt story. Water is a much more effective mechanism to transfer heat to the ice compared to the atmosphere. This is seen in mass balance buoys presented by Don Perovich and colleagues at the U.S. Army Cold Regions Research and Engineering Lab that measure the relative contributions by the ocean and atmosphere to summer melt[iii]. […] near the ice edge bottom melting tends to dominate."

It isn't clear yet whether transport of warm water into the Arctic is contributing much to the melting from below. Lindsay: "I don't know if it is possible to measure any additional heat being drawn from the warm Atlantic layer below the cold halocline." Meier mentions some indications for transport into the Arctic: "This ocean contribution [to the melting] is due to in situ ocean warming or transport of warm water into the Arctic. There are some indications of influxes of warmer surface and near-surface water in the Pacific region (e.g. by W. Maslowski at the U.S. Naval Postgraduate School), but most of the heating is in situ due to solar insolation[iv]. Steele et al. also find that near the ice edge, bottom melt accounts for 2/3 of the thickness melt vs. 1/3 for surface melt from the atmosphere."

This 1/3 vs. 2/3 ratio can't be used for the Arctic as a whole yet. Lindsay: "I don't agree that 2/3 of the melt comes from the ocean. How do we know that?" Adding: "If there is a trend in ocean heat flux I am not aware of it, except for solar heat absorbed by the ocean that subsequently melts ice."

Solar insolation

Nevertheless a lot of the heat that is causing the seasonal melting now seems to come from in situ solar heating. Like Meier explains: "Even though the solar insolation maximum occurs when much of the Arctic Ocean is still ice-covered (i.e. June 21), a significant amount of heat is absorbed through the ocean. Buoy data[v] surface temperatures are >5°C, which is 7+°C above the melting point for the ocean water. These are surface temperatures, but the heat extends down several meters (via communication with Mike Steele). That is a lot of heat."

With lots of the heat coming from in situ solar heating in the summer, a few processes are relevant: early snow melting in spring leading to melt ponds in the sea ice, opening the Arctic ocean for incoming solar radiation, which then melts the ice from both above and below the ice. Clouds are also an important player in these processes, although not much is known about the trends in clouds in this area. Curry: "With regards to the summer minimum, the clouds are contributing and seem to have been a major factor during 2007. Clouds are much more powerful radiatively than CO_2, so if we are talking about radiative forcing, clouds should be front and center in the discussion." This doesn't mean though that Curry is thinking that clouds in general are the main driver for summer melting: "This response does not imply that I think clouds are the only or even the main driver of the summer sea ice minimum."

Lindsay: "It is very hard to really know what the long-term changes in the cloud radiative forcing is in the central Arctic, in part because satellite retrievals of cloud properties can be biased by changing surface properties, so if the surface changes (less ice) is the change in estimated cloud properties real or just an artifact?" Slightly later in the discussion Lindsay adds this: "As Judith says, clouds are the big player in radiative fluxes. How they are changing in response to changing ice in amount, composition, and vertical structure is still an open research question, so we don't really know if cloud changes will be a positive or a negative feedback. Because they are so important I would not be surprised if they are found to be at least part of the source of the ice melt, but because cloud temperature and properties may change due to changing surface properties, sorting out cause and effect could be difficult."

So snow and ice feedback could both be positive leading to larger melting in the summer. Lindsay: "Atmospheric fluxes are highly variable and accurately determining a long-term trend is difficult. A possible strong feedback is the lower albedo of melting snow in the spring so that an earlier onset of melt is amplified with earlier snow melt, earlier melt pond formation, and earlier lower albedo of bare ice[vi] which would amplify melt. In terms of melt, by far the largest component is the solar flux, so understanding how the surface albedo changes is crucial."

Ice growth in winter

The extra heat in the oceans is quickly lost in the autumn though and first year ice is growing faster than multi-year ice. As Curry explains: "Ice volume increase during winter can actually be larger for first year (FY) ice than for a field dominated by multi-year (MY) ice. Thin ice grows at a much faster rate than thick ice. The change in ice volume for MY-dominated vs. FY dominated during summer is trickier. Thicker ice actually starts melting a bit earlier than thin ice owing to the larger sensible heat loss over the thin ice, but the thin ice may entirely disappear over the course of the summer by melting. A key issue is whether the FY ice can survive through the summer. This depends on the local thermodynamics, and also the export [through the Fram Strait] and also breakup induced by a big cyclonic storm. So following the time variation of the second year ice is another key to understanding what is going on (thermodynamics vs dynamics/export)[vii].

Lindsay: "A lot of different aspects of the system are changing and I can't say which one is dominant, if any. I am not aware of observations that show the heat flux from the ocean is increasing. A lot of solar heat is now being dumped into the ocean in late summer, but much of this heat is quickly lost to space in the fall, so the impact on winter growth may be modest, again the thin ice growth rate feedback. How much of this new summer heat is sequestered and slows ice growth all winter is an open research question."

Summary

Over the last 30+ years, Arctic sea ice has declined precipitously, particularly during summer. Summer ice extent has decreased by ~50%, including most of the older, thicker ice. Sea ice volume has decreased even more, with the monthly averaged ice volume for September 2012 of 3,400 km3, which is 72% lower than the mean over the period. There is no disagreement about these facts. However, it is less clear what are the main processes that caused the decline.

The discussants agree that relatively little heat (~0.5 W/m2) is necessary to explain the decline of Arctic sea ice in the past three decades. These changes are so small that our observational systems are unable (yet) to detect the main sources for this trend.

The discussants agree that in general melting from the ocean is much more effective than melting from the air. However there is little evidence that transport from either the Atlantic or the Pacific contributed much to the melting in the past decades.

A number of processes seems relevant: earlier snow melting in spring leads to melt ponds in the sea ice, opening the Arctic ocean for incoming solar radiation, which then melts the ice from both above and below the ice. Clouds are also an important player in these processes, although not much is known about the trends in clouds in this area.

The discussants stress that it's difficult to separate cause and effect. The major forcings and feedbacks influencing the Artic sea ice can change from year to year.

	Meier	Curry	Lindsay
The decline in sea ice *extent* since 1979 is very well documented/undisputed	5	5	5
The decline in sea ice *volume* since 1979 is very well documented/undisputed	5	4	5
Two thirds of the melting each summer is taking place from below the ice	3	x	x
Earlier snow melt in spring is playing a big role in the summer melting	4	4	4
By far the largest component causing the seasonal melting is the solar flux	5	5	5
The influx of warmer waters from the Atlantic has played a minor role in causing the decline in Arctic sea ice	x	x	x

Scores (don't know=x, very unlikely=1, unlikely=2, as likely as not=3, likely=4, very likely=5,)

2. How unusual is the current decline in historical perspective?

Lindsay is most outspoken that the current decline is remarkable in historical perspective. "The current decline in ice extent and volume is highly unusual. Maybe the best way to show this is in the consistency in the trends. The linear trend in the September ice thickness from 1987 to 2012 explains 90% of the variability, much more than any other comparable interval since 1948. The observational record for sea ice is more spotty before this time, though researchers are piecing together a more comprehensive picture from various ship observations. So far that picture doesn't suggest that large variations in sea ice extent were anything but regional over the last 120 years or so."

Curry on the other hand is much more focused on the uncertainties before the satellite measurements (1979) start. "The conventional understanding of Arctic sea ice extent shows a general retreat of seasonal ice since about 1900, and accelerated retreat of both seasonal and annual ice during the latter half of the 20th century. Hints that this understanding may be overly simplistic in view of the uncertainties and ambiguities in the period prior to satellites are described in this presentation[viii] by John Walsh about plans for a gridded sea ice product back to 1870. Further, I've recently had some discussions about this with a historian that is investigating historical reports of sea ice extend during the period 1920-1950. He has found reports of reduced wintertime extent during this period, and a general lack of data from the Russian sector. While this material is not yet published, it reminds us that prior to 1979, we do not have a reliable data set of global sea ice extent. The lack of such a data set hampers our ability to test our ideas about the impact of natural variability versus anthropogenic forcing on sea ice variability and change."

Meier is closer to Lindsay. He thinks the historical evidence points towards lower ice extent in the 1930s but these changes were more regional: "While our most complete dataset, the one we have the highest confidence in, is the passive microwave record, there is fairly complete coverage from operational ice charts back to at least the mid-1950s. And there are Russian ice charts for the Eurasian Arctic back to the early 1930s. Though not complete, these do extend the record and I think provide some sense of the interannual and decadal natural variability of the ice. There are indications of lower ice in the 1930s in the Russian Arctic[ix], suggesting the influence of a multi-decadal cycle (AMO?), at least in the Russian Arctic. But the data show a different character in terms of the seasonality and regionality of the lower ice conditions compared to the recent decline." In another comments he adds: "Before the 1950s, the 1930s are often mentioned as a warm period. However, this is primarily in the Atlantic region, where observations were more common. Ice charts from the

Denmark[x] and Russia, indicate some periods of low summer ice, but on a more regional scale than we see now."

Holocene
Going back further in time, both Lindsay and Meier refer to the reconstruction of Kinnard for the last 1.5 millennium: "A reconstruction based on proxy records suggest that sea ice extent is now the lowest in 1450 years[xi]." Even further back goes a review article of Polyak[xii] which concludes: "This ice loss appears to be unmatched over at least the last few thousand years and unexplainable by any of the known natural variabilities." That same review of longer records indicates that the last time the Arctic had little or no summer ice was during the Holocene Thermal Maximum (~8000 years before present).

There has been little discussion about the uniqueness of the recent decline and the discussants indicate they are no expert on this matter. Meier has looked into the question though because at his institute NSIDC they receive a lot of questions about this. He offers an interesting thought experiment about what it could mean that the Arctic has been ice free in the past (~8000 ybp). "There are (at least) two ways of looking at it: If the Arctic has been ice-free during summer in the past, obviously it was due to natural forcing, so the current decline could also be due to natural forcing. If the Arctic has been ice-free during summer in the past due to natural forcing then anthropogenic forcing of a similar magnitude will have a similar effect. The first view is not implausible on its face, but it is simplistic because it doesn't consider that the same result could be due to the same causes. Lightning starts forest fires, but that doesn't rule out that a forest fire may be due to human actions. The second view is much more useful in my view because it has potential predictive value at least for the equilibrium state of the ice cover under a given forcing. For example, in the Holocene (~8000 ybp), the Arctic Ocean likely had ice-free or near ice-free summers and temperatures were similar to, maybe still a bit higher, than Arctic temperatures in recent years. Thus, the decline we're seeing is entirely expected and we would expect to see it continue to near-zero summer extent in the coming years. The timing is still uncertain but it changes things from an "if the Arctic loses summer sea ice" to "when the Arctic loses summer sea ice".

Summary
Lindsay and Meier have more confidence that the current decline is unprecedented in historical context. Curry stressed the lack of data before 1979 which hampers our understanding of the state of Arctic sea ice in the past. Meier on the other hand mentioned several studies that shed light on past sea ice conditions and how they differ from the current situation. The participants agree that during the Holocene Thermal Maximum (around 8000 ybp) the Arctic likely was ice free or near ice free as well in the summer. At that time temperatures in the Arctic were similar as today or even higher.

	Meier	Curry	Lindsay
The current decline in ice extent is unprecedented in the *last century*	5	4	5
The current decline in ice extent is unprecedented in *the last two millennia*	3	x	3
The current decline in ice extent is unprecedented in the *Holocene*	3	x	2

Scores (don't know=x, very unlikely=1, unlikely=2, as likely as not=3, likely=4, very likely=5,)

3. Is there evidence for a substantial role of natural variability?

According to Lindsay and Meier, the short answer to this question is 'no'. Curry is far less sure about this, emphasizing our lack of knowledge about the issue. So it is fair to say that there is disagreement

about this topic.
Lindsay stated: “I think we all agree that the AO (Arctic Oscillation), NAO (North Atlantic Oscillation), and PDO (Pacific Decadal Oscillation) have little role in the long-term decline. I am less certain about the AMO (Atlantic Multidecadal Oscillation), although I am inclined to think it too is a minor player.” Curry on the other hand said: “Large scale atmospheric and ocean circulations vary on multi-decadal time scales, which influence circulation regions on shorter time scales as well, which among other things influences sea ice characteristics. Untangling how all this works has received far too little attention in my opinion.”

The kick
Let’s first discuss why Meier and Lindsay don’t see a large role for natural oscillations. They acknowledge that the AO and other oscillations have influence on the sea ice but stress that this influence now seems minor. For example all three see a role for the AO when the recent decline started in the late 80s/early 90s. Curry wrote in her guest blog: “During the late 1980s and early 1990s, the circulation patterns favored the motion of older, thicker sea ice out of the Arctic. This set the stage for the general decline in Arctic sea ice extent starting in the 1990’s.” Lindsay and Meier seem to agree with this view on the decline. In a comment Lindsay wrote: “[…] I once wrote a paper that raised the question of whether a tipping point had been passed in the late 1980‘s, when the current decline in ice thickness in the arctic ocean began in earnest, coincident with a shift in the AO, a shift I called “the kick” which started the decline. Despite a return to normal AO conditions the decline continued.” And Meier in a more general explanation wrote: “For example, the AO has been observed to have a large effect on summer ice condition. When the winter AO is positive, thick ice tends to get pushed out of the Arctic through the Fram Strait, leaving a thinner ice pack the following summer that is more likely to melt completely. The converse is true for a negative AO. However, the AO typically has a 3-7 year cycle, which does not correspond to the long-term trend. In addition, in recent years, the influence of the AO appears to have been broken, or at least weakened. For example, the 2009-2010 winter had the lowest AO on record (since 1950), and yet the summer 2010 minimum was among the lowest in the satellite record[xiii].”

So the discussants agree that the AO likely played a role in the early 90s to start the decline by pushing older and thicker ice out of the Arctic through the Fram Strait. Since then the correlation between the AO and Arctic ice has diminished, convincing Meier and Lindsay it now has a smaller role. In his guest blog Lindsay wrote: “Evidence from models[xiv] indicates that the AO may not play much of a role in sea ice variability. That same study suggests that the AMO may indeed play a significant role in sea ice decline and that as much as 3%/decade of the 10%/decade trend in September sea ice extent between 1979-2010 may be due to AMO variability. There is also some observational evidence that sea ice extent may be influenced by the AMO but none of this evidence suggest that an arctic-wide change in ice extent as seen over the last decade is possible due to these type of modes of natural variability alone. It also appears ice thickness within the Arctic Ocean is less closely tied to the AMO.”

Thin ice
Meier thinks the thinner ice has a different interaction with natural oscillations. Meier: “What is different now? The ice is thinner. Thinner ice is more easily moved around and out of the Arctic, is more easily broken up into smaller floes (that are more susceptible to melt), and is more easily melted completely during summer. We’ve seen this in recent years in the Beaufort Sea. Historically, this region has been a nursery of old thick ice and the ice moved in a clockwise direction in the Beaufort Gyre aging and thickening over many years. However, in recent years, the ice in the gyre has not survived the summer. The nursery has become a graveyard. There is likely some influence of ocean waters, which may have a cyclical natural varying component, but the thinner, more broken ice is the larger factor. Our expectations for how the ice responds to natural variability is based upon a thicker ice cover, which may no longer be valid.”

Another reason Lindsay doesn't see a large influence of natural variability is that the sea ice thickness and/or volume (the preferred metric for Lindsay) is much less influenced by natural variability than the sea ice extent. "While natural variability is very important for determining the ice extent, primarily through the action of the winds, I see a very consistent trend in the mean ice thickness with relatively little year-to-year variations. So while natural variability can strongly influence the ice area and extent, I doubt there is a strong component in the variability of the mean ice thickness within the Arctic Ocean."

Curry on the other hand sees a large role for so called climate shifts, a concept that has recently been picked up by papers of Swanson and Tsonis[xv] and David Douglass[xvi]. These shifts are related to several natural oscillations, although the physical processes behind it are far from clear yet. In her guest blog she wrote: "In 2001/2002, a hemispheric shift in the teleconnection indices occurred, which accelerated the downward trend. A local regime shift occurred in the Arctic during 2007, triggered by summertime weather patterns conspired to warm and melt the sea ice. The loss of multi-year ice during 2007 has resulted in all the minima since then being well below normal, with a high amplitude seasonal cycle. After 2007, there was another step loss in ice volume in 2010. In 2012, the basic pattern of this new regime was given a 'kick' by a large cyclonic storm in early August."

Models

Another difference of opinion is originating in the confidence one should have in models. Lindsay defends the models: "To refute the evidence from models, one would have to show that they wildly underestimate natural variability (with regard to sea ice). Even in the NCAR CCSM4 which is one of the CMIP5 models with the highest "natural" variability, the sea ice extent trend over the last 30 years is still 50% due to greenhouse gases[xvii]." Adding later: "It is possible there are large unknown sources of long-term natural variability, but I think the models and the observations show CO2 is the major cause of the decline. Other sources of large long-term variability (say 30 to 100 years) that could contribute substantially to the decline are mostly speculation."

Curry on the other hand does indeed think that models underestimate natural variability: "The relatively high attribution to AGW comes from climate models, which have substantial problems in simulating the Arctic climate […]. Not to mention that these climate models underestimate natural internal variability on multi-decadal timescales. […] I note that my group has just submitted a paper for publication analyzing the CMIP5 simulations of arctic sea ice. I am frankly trying to figure out how these models manage to produce any kind of sensible sea ice given that most of these models are biased cold (many are biased cold by 2°C or more). Our old friend 'model calibration' I assume, whereby 5 wrongs might make a 'right'."

So pretty strong disagreement here, mainly between Lindsay and Curry. Meier gives some consolation pointing out how complicated the sea ice system and its interaction with the AO might be: "One thing that I think is clear is that the sea ice system is complicated and that many factors that influence each other are changing, making separating them out difficult. Going back to a point I made earlier, I think an intriguing aspect is how the influence of natural variability on the sea ice (and vice versa) is changing. In other words, AO affects sea ice, but how is that effect changing with a changing ice cover and are the changes in the ice in turn influence the AO?"

Summary

The discussants agree that a shift in the Arctic Oscillation (AO) in the late 80s seemed to have started the decline. A positive AO, especially in winter, pushed older thicker ice out of the Arctic through the Fram Strait. When the AO went back to normal however, the decline in sea ice continued. Meier and Lindsay conclude from this that oscillations like the AO, but also the NAO and PDO, probably played a minor role in the continuing decline. Model simulations suggest that the AMO might have contributed between 5% and 30% of the melting. Curry is not so sure about this. She mentions a hemispheric climate shift in 2001 that accelerated the decline followed by a local regime shift in 2007, that has resulted in all the minima since then being well below normal, with a high amplitude seasonal cycle. Lindsay and Meier also have more confidence in the models than Curry. Lindsay said it isn't likely that they hugely underestimate natural variability, but this is exactly what Curry thinks the models do.

	Meier	Curry	Lindsay
A shift in the AO to positive values started the decline in the early 90s	4	4	4
Now that the ice is thinner, the effect of natural oscillations is much smaller	4	3	4
Models underestimate natural variability considerably	2	5	1

Scores (don't know=x, very unlikely=1, unlikely=2, as likely as not=3, likely=4, very likely=5,)

4. What is the role of 'global warming'?

This question is of course closely related to the question about natural variability. So the positions on this topic are similar with Lindsay and Meier seeing more evidence for a large role of global warming than Curry. This is based on evidence from both observations and models.

In his guest blog Lindsay points out that the Arctic ice trends are correlated with temperature trends on the Northern Hemisphere. "One piece of evidence […] is the high correlation (R = -0.72, 57 years through 2011) between the rate of melt (including export) in the Arctic Ocean and melt season (May to September) surface temperatures in the rest of the hemisphere, from 20N to 60N (NCEP-R1). The surface temperatures south of the Arctic are likely less influenced by ice loss and the trends are likely more influenced by global forcings. Sea ice basically responds to hemispheric conditions and is not on its own trajectory."

Meier has similar arguments: "The evidence for a substantial role of "global warming" in the current sea ice decline comes from the fact that the decline (1) correlates with the global warming temperatures over the past several decades, (2) is outside the range of normal variability over the past several decades and likely over the past several centuries, (3) the decline is pan-Arctic, with all regions experiencing declines throughout all or most of the year." And later in a comment: "I base my view on the decline of not only summer extent but the rapid loss of old ice and the thinning of the ice cover, along with the apparent change in the response of the ice to natural fluctuations (such as the AO mode, as I discussed in my previous comment). Of course, natural variations have played a role and will continue to do so, but I don't see a large enough effect to account for a substantial fraction of the observed change."

Curry stated in her guest blog that the "lack of data [before 1979] hampers our ability to test ideas on contribution of natural variability versus anthropogenic forcing on sea ice decline". However, during the discussion and also in her blog she highlights the role of natural variability in the current sea ice decline. In her post she talks about the "basic story" as she sees it and she then sums up all kind of natural factors and shifts. This leads to the following statement about the role of global warming: "So, what is the contribution of anthropogenic global warming to all this? It's difficult to separate it out. The polar regions are extra sensitive to CO2 forcing and water vapor feedback, owing to the low amounts of water vapor. However, any radiative forcing from greenhouse gases is swamped by inter-annual variability in cloud radiative forcing. In the bigger picture sense, greenhouse forcing is involved in complex nonlinear ways with the climate regime shifts. So there is undoubtedly a contribution from CO2 forcing, but it is difficult to find any particular signal in this year's (2012, red.) record minimum, other than the contribution of greenhouse warming to a longer term trend." With the last sentence Curry's view comes closer though to that of Meier and Lindsay.

She acknowledges the role of greenhouse (global) warming in the decline of Arctic sea ice, although as we will see she tends towards a lower contribution of greenhouse gases than Lindsay and Meier.

Substantial

Models again play a role in the view of Meier and Lindsay. As Meier wrote: "Also, model simulations of sea ice cover consistently show a response of declining sea ice to increasing GHGs (albeit slower than the observed decline); conversely, model runs over the last 30 years without GHG forcing do not show a decline[xviii]. Finally, there does not appear to be a mechanism to sufficiently explain the long-term decline without including the effect of GHGs[xix]."

Lindsay again is the clearest about a large role for global warming: "The evidence for a substantial role of "global warming" in the current Arctic sea ice decline is very strong, both from observations and from modeling studies. Of course neither can "prove" the role of greenhouse gases but there is overwhelming evidence it is true. […] For those that think this is not the case, they need to show some evidence that there are alternative explanations. Comparing ice volume instead of sea ice extent greatly reduces the natural variability compared to the trend and shows an earlier and more definitive separation than ice area between models run with or without increased greenhouse gas forcings[xx]."

Curry on the other hand doesn't place a lot of trust in model simulations of Arctic climate (see section 3 above).

Summary

There is disagreement about the role of global warming. Both Lindsay and Meier sum up evidence for a large role of "global warming" in the current decline in sea ice. Lindsay mentions the good correlation with the Northern Hemispheric temperatures, showing that the sea ice is not on its own regional trajectory but follows the trend of a larger area. Meier notes the fact that the warming now is pan-Arctic and outside the range of natural variability for the last few centuries. Curry acknowledges a role for global warming to the longer term trend. But at the same time she notes that locally any radiative forcing from greenhouse gases is swamped by inter-annual variability in cloud radiative forcing.

	Meier	Curry	Lindsay
The evidence for a substantial role of "global warming" in the current Arctic sea ice decline is very strong	5	4	5

Scores (don't know=x, very unlikely=1, unlikely=2, as likely as not=3, likely=4, very likely=5,)

5. Quantification of the anthropogenic contribution to sea ice decline

Curry made what she called a 'wishy washy' statement about the attribution of the melting to anthropogenic forcing. She wrote: "So . . . what is the bottom line on the attribution of the recent sea ice melt? My assessment is that it is likely (>66% likelihood) that there is 50-50 split between natural variability and anthropogenic forcing, with +/-20% range. Why such a 'wishy washy' statement with large error bars? Well, observations are ambiguous, models are inadequate, and our understanding of the complex interactions of the climate system is incomplete."

Later in a comment she simplified this statement a bit: "I think a simpler way to look at this would be to attempt to put bounds on the AGW contribution to the recent sea ice melt. I propose a range of 30-70%. Walt and Ron seem to be above 50% but not going higher than 70%." And in another comment she said: "If I am interpreting their [Lindsay's and Meier's] assessments correctly, am I correct to infer that we are all in agreement within the range of uncertainty that we would each acknowledge? The disagreement seems to arise if we are each forced to pick a single attribution value: mine would be 50%; I infer that Lindsay's in particular would be higher. But given the uncertainties, is there any particular reason to force this level of specificity and highlight disagreements?"

Meier replied that a 50-70% would be reasonable. "The 50-70% range for GHGs that Judith mentions is probably a reasonable spread in capturing the potential range. I would lean more toward the high side of that range because I don't see the AMO and PDO having a large magnitude influence on summer ice. The AO does have a larger influence, but that has largely been lost in recent years."

Note that here they refer to a different range. Curry's range is wider, 30-70%. Lindsay replied that he also accepts a large uncertainty: "I agree with Judith that the percent decline in sea ice due to greenhouse gases is rather uncertain. It depends on the time intervals considered for the base case and current state (how much natural variability is averaged out)."

Curry even added she can't think of many or even any climate scientist that would go either above 70% or below 30%. "One of the complaints from the comments is that the scientists with 'extreme' views (i.e. outside of this range) were not included. I wonder if Peter Wadhams would have gone above 70%? I am trying to think of any published scientists working on sea ice or Arctic climate dynamics that would go below 30%, and I can't think of any." However, both Lindsay and Meier quoted Day et al (2011)[xxi] in support of their position, who estimate natural variability having caused between 5% and 30% of the decline, which would allow for the anthropogenic contribution to be up to 95%.

Lindsay separates his estimates for ice extent and ice volume, leaning towards high percentages for ice volume: "I come back to the observation that ice volume is a much more consistent measure of the ice cover, showing much less year to year variability compared to the trend than ice extent or area. The CCSM3 model, for example, shows a clear separation in ice volume between the control and the A1B scenario as early as 1985, 10 to 15 years before the separation in ice extent[xxii]. The decline in volume is consistent with the PIOMAS estimates of ice volume (which is tied to the observed past weather and ice extent), given the uncertainties in both data sources. CCSM4 simulations show about a 50% decline in ice volume since the 1960's with a typical ensemble spread on the order of 15%, so the CCSM4 runs indicate the decline in ice volume is about 3 times the natural variability, or about 70% of the decline is due to greenhouse gases. The decline in volume seen in the PIOMAS simulations is also very consistent, particularly if one focuses just on the Arctic Ocean since the late 1980's. So I would go on the high side of the percentage loss due to greenhouse gases for ice volume and less for ice extent, maybe near 50%."

Speculate

Later in the discussion all three acknowledged a great deal of uncertainty when making attribution statements. Meier for example wrote: "There seems to be a lot of wrangling over exactly what fraction of the observed change is attributable to GHGs vs. natural and other human (e.g., black carbon). There is clearly still uncertainty in any estimates and the models and data are not to point where we can pin a number with great accuracy. Judith is more on the lower end, rightly pointing out the myriad natural factors. Ron and I tend toward the higher end. I base my view on the decline of not only summer extent but the rapid loss of old ice and the thinning of the ice cover, along with the apparent change in the response of the ice to natural fluctuations (such as the AO mode, as I discussed in my previous comment). Of course, natural variations have played a role and will continue to do so, but I don't a large enough effect to account for a substantial fraction of the observed change."

And Lindsay wrote: "About the attribution of the decline to AGW vs. natural. The fact is we don't really know and all we can do is speculate. That is not really science. Also the question is a little ambiguous. Are we referring to a linear trend, and if so over what period, or to a change for a particular year and against what base line? Do we assume natural variability is only contributing to the decline, or might it also slow it? So trying to put definite numbers on the ratio for the observed climate, even the uncertainty, is likely a futile effort. This can be done for ensemble model simulations of the climate, with all of the caveats that go with such studies, and the answer is a statistical summary for the model used, not a real-world analysis."

Curry defended her focus on uncertainty by saying that "[…] when my uncertainty level seems higher than others, it is because I have a longer list of known unknowns than most others, which is traced back to my own publications and my service on the committees listed above."

Summary
The participants agree it is unlikely the contribution of greenhouse gases to the recent decline is lower than 30%. Curry even said she wouldn't know any publishing climate scientist going lower than 30%. Curry proposed a range of 30 to 70% greenhouse gas contribution to the recent decline in sea ice extent. Her best estimate would be 50%. Lindsay agreed with this best estimate of 50% for extent. He added though that sea ice volume is his preferred metric because it shows less year to year variability. For sea ice volume he would go higher, say 70%. Meier proposed a smaller range of 50 to 70%.

	Meier %	Curry %	Lindsay %
What is your preferred *range* w.r.t. the contributions of *anthropogenic forcing* to the decline in *sea ice extent*?	50-95%	30-70%	30-95%
What is your preferred *range* w.r.t. the contributions of *anthropogenic forcing* to the decline in *sea ice volume*?	50-95%	30-70%	30-95%

Scores (don't know=x, very unlikely=1, unlikely=2, as likely as not=3, likely=4, very likely=5,)

6. Could the Arctic be ice free in the near future?

Meier explained why he is not very enthusiastic about Peter Wadhams' prediction that the Arctic could be ice free within a few years. "While I won't totally dismiss the possibility, I think it is a very low probability event. My rationale is that getting there relies on continuing to lose volume at the same rate as we've done over the last decade or so. I think there are a couple of very good reasons why this is unlikely. First, as Judith has particularly noted, there have been some extreme events in recent years that have helped kick down the summer ice and remove old ice. While I think there is room to debate how large of an effect these have had, we can't depend on such events to happen in a timely manner in the next few years. But the larger reason for my doubts is that the rapid losses have come from the Siberian and Alaskan regions of the Arctic. The region along northern Greenland and Canadian Archipelago have not lost much summer ice – for good reason. The predominant ice circulation pushes ice toward those coasts resulting in thick ice that tends to get replenished. In other words, we've seen a rapid decline in the "easy" ice to lose, but now we're getting to the "more difficult" ice. I think it's likely that that will go more slowly."

Although Lindsay agrees with Meier about the 'Wadham hypothesis', he does think the summers could be ice free within a decade or two. "The Arctic will likely be largely ice free at the end of some summers within a decade or two. Small bits of ice might remain some years, but they may not matter for much."

Not surprisingly Curry is most reluctant in providing an estimate. She writes in her blog that: "prediction of sea ice is hostage to predictions of the chaotic atmospheric and oceanic dynamics." In a comment she writes: "Pretending that extrapolating an observed trend or that CMIP5 simulations will produce a useful decadal prediction of sea ice is pointless (well there is a potential point but it is to mislead)." And in a comment to James Annan: "My point is that I don't know with any high level of confidence what the sea ice will look like in 10 years or 100 years." And finally she concludes that: "On timescales of two decades, I expect the natural variability to dominate, and this could still take us in either direction (more or less ice)."

Definition

Curry was also a bit annoyed about the generally accepted definition of ice-free. "[…] 'ice free' is usually taken to mean less than 1 million sq. km. This is far from 'ice free' in actuality (I find this use of 'ice free' to be highly misleading). So what is the point of talking about some sort of 'tipping' point, when even during summer, the Arctic Ocean is not really projected to be ice free?"

Following up from Curry in regards to what "ice-free" means, Meier agreed that this isn't a particularly well-defined term, but he thinks it is nonetheless useful for thinking about changes in the ice cover and its impact. "It will indeed be difficult to reach completely ice-free (zero) ice because of the geography and dynamics of the system. Semi-enclosed bays and channels (e.g., the Canadian Archipelago) are more resilient to break-up and melt and, as I mentioned a previous post, the Greenland side of the Arctic gets replenished by ice moving across from Siberia. This ice can pile up into thick (several meters) ridges that are difficult to break up and melt completely." Curry agrees: "This definition is used because it is very difficult to melt the thick ice around the Canadian Archipelago. And the issue of 'ice free' in the 21st century is pretty much a non-issue if your require this thick ice to disappear."

For practical purposes Meier still thinks the definition is valid. "Instead of simply saying "ice-free", my views is that it should be described as "ice-free for all practical purposes". To me this means: seeing blue instead of white throughout the Arctic Ocean (except along the coasts), allowing ships to operate within the Arctic Ocean with little chance of seeing substantial ice, having a significant effect on the Arctic ecosystem, and having a significant effect on Arctic. (The last two are likely already occurring.) […] So I'm not worried too much about what we mean by "ice-free" or what specific number we put on it – that's for gamblers placing bets to quibble about."

Tipping point

The discussants agree there doesn't seem to be a tipping point and that sea ice could recover pretty soon if the circumstances are right. Lindsay: "Current research does not support the notion of any "tipping" points for summer sea ice so if we somehow magically could turn off the forcing that comes from greenhouse gases, sea ice would likely grow back relatively quickly. Unfortunately that is not likely to happen. Winter ice will remain for a long time, a century or more. How long probably depends mostly on the future rate of greenhouse gas emissions." And later in a comment: "I now believe a tipping point for summer sea ice is not a good way to characterize the system. The sea ice in the Arctic responds to global forcing in the atmosphere and ocean and is not on its own trajectory. A number of studies have supported this conclusion." Curry wrote something similar: "The first issue to debunk is that an 'ice free' Arctic is some sort of 'tipping point.' A number of recent studies find that in models, the loss of summer sea ice cover is highly reversible."

Also Meier and Lindsay point out that we might have several years with low ice-extent (or even near ice free conditions) followed by years with a higher extent, implicating that a 'first' year of being ice-free is not particularly meaningful. Meier indicates in his blog that IPCC models that match historical records indicate ice-free conditions in 2030-2050.

For the near future anything can happen according to Curry: "Whereas sea ice models are becoming quite sophisticated, most recently in terms of the radiative transfer, melt ponds, and aerosols, prediction of sea ice is hostage to predictions of the chaotic atmospheric and oceanic dynamics. For the next two decades, natural variability will almost certainly trump any direct effects from anthropogenic warming by a long shot. The current sea ice situation does not seem stable, but it is not at all clear whether we can expect a reversion to the (more recently) normal state or yet a larger ice loss." And then, Curry adds, there are the known unknowns: "what solar radiation will do (looks like cooling), volcanoes are always a wild card, and then there are the less known unknowns such as cosmic ray effects, magnetic field effects, etc. And in terms of climate shifts, there may be something happening on much longer time scales (e.g. the Atlantic Meridional Overturning Circulation) that could influence the next climate regime shift. Focusing on CO2 as the dominant influence on the time scale of two decades seems very misguided to me."

Lindsay though thinks the CO2 induced global warming will continue to cause a decline in the ice volume, even on a time scale of a decade or two. "I agree with Walt that the summer ice will come and go for a number of years, depending on the weather and the winds, but when it first goes to near zero is quite hard to predict."

Meier "wholeheartedly" agrees with Curry that decadal prediction of sea ice is going be very difficult. "I have been involved in several meetings about the issue including the one that is the basis of the NRC report Judith references (Ron was also a participant). I will note that among those most skeptical of the models' capability to capture decadal variability are the modelers themselves."

The discussants agree that for a long time the Arctic will refreeze in winter. Curry notes that "sea ice would continue to freeze and thaw on an annual cycle". Later in a comment she explains: "The massive cooling during the polar night causes substantial heat loss, which on land results in surface temperatures of -40°C and colder. Sea water in the Arctic Ocean freezes at a temp slightly warmer than -2°C. The only conceivable way to keep the Arctic Ocean ice free is to bring in much warmer ocean water from lower latitudes. Unless the geography of the Arctic basin dramatically changes, e.g. Alaska disappears, there is no way for this to happen. I don't think that anyone would dispute these points." Lindsay: "Winter ice will remain for a long time, a century or more. How long probably depends mostly on the future rate of greenhouse gas emissions."

Summary

None of the participants is very enthusiastic about the idea that the Arctic could be ice free in the summer within a few years. Meier explained that so far the "easy" ice has melted but that now we're getting to the "more difficult" ice north of Greenland en the Canadian Archipelago. "The predominant ice circulation pushes ice toward those coasts resulting in thick ice that tends to get replenished."

Lindsay is most confident that even on a time scale of one or two decades greenhouse forcing should cause a further decline. Curry emphasized that on this time scale natural fluctuations will dominate the effect of CO2. For her a reverse of the trend is therefore possible. Meier "wholeheartedly" agreed with Curry that decadal prediction of sea ice is going be very difficult.

Curry stated that the currently used definition of "ice free" (being less than 1 million km2 of ice) is misleading as it is not really ice free. Meier defended the definition as being valid for all practical purposes like ship navigation, the albedo feedback and impacts on the ecosystem.

None of the participants believe in a tipping point. Lindsay noted that if we magically could turn off the forcing the sea ice could recover pretty quickly. Lindsay: "Unfortunately that is not likely to happen."

	Meier	Curry	Lindsay
The Arctic could be ice-free in a few years	1	1	1
The sea ice could (partly) recover in the next two decades due to natural variability	2	3	1

What is the most likely period that the Arctic will be ice free for the first time?	2030-2050	x	2020-2050

Scores (don't know=x, very unlikely=1, unlikely=2, as likely as not=3, likely=4, very likely=5,)

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