**1. Introduction**

Arctic sea ice extent has declined by more than 40% since 1979 during summer (e.g. Stroeve et al. 2012; Serreze and Stroeve 2015; Comiso et al. 2017), primarily as a consequence of greenhouse gas forcing (Notz and Marotzke 2012) but also internal variability (Ding et al. 2017). While this trend is greatest in summer, substantial losses are observed throughout the year (Cavalieri and Parkinson 2012) resulting in an ice season duration that is up to 3 months shorter in some regions (Stammerjohn et al. 2012). Reduced ice area is accompanied by a greater fraction of younger ice (Nghiem et al. 2006; Maslanik et al. 2007a, 2011), which reduces the mean thickness of the basin ice pack (Kwok and Rothrock 2009; Kwok et al. 2009; Lang et al. 2017). As a result, the estimated negative trend in sea ice volume (-27.9% per decade) is about twice as large as the trend in sea ice area (-14.2% per decade; Overland and Wang 2013).

Output from many climate models suggests that the Arctic sea ice cover will not retreat in a steady manner, but will likely fluctuate more as it diminishes, punctuated by occasional Rapid Ice Loss Events (RILEs; Holland et al. 2006; Döscher and Koenigk 2013). The overall decline in ice cover is expected to continue (Collins et al. 2013), and the Arctic may become seasonally ice-free within a few decades, depending on emissions pathway (Stroeve et al. 2007; Wang and Overland 2009; 2012; Massonet et al. 2012; Wang and Overland 2012; Overland and Wang 2013; Jahn et al. 2016; Notz and Stroeve 2016). However, internal variability confounds prediction of this timing (Stocker et al. 2013; Swart et al. 2015; Jahn et al. 2016; Labe et al. 2018), and even the definition of ice-free differs among Arctic stakeholders (Ridley et al. 2016). Nonetheless, navigation through the Arctic has already increased in frequency as a result of this decline (Melia 2016; Eguíluz et al. 2016), and even more trade routes associated with the increased ice-free season are expected by the end of the 21st century (Aksenov et al. 2015; Stephenson and Smith 2013).

As the Arctic sea ice pack thins and retreats, multi-year ice is being lost and there is consequently a larger proportion of seasonal, thin first-year ice (Kwok et al., 2010, Maykut 1978; Holland et al. 2006). Overall thinner ice may result in an ice pack that exhibits greater inter-annual variability (Maslanik et al. 2007b; Goosse et al. 2009; Notz 2009; Kay et al. 2011; Holland and Stroeve 2011; Döscher and Koenigk 2013), at least partially due to enhanced ice growth and melt (Maykut 1978; Holland et al. 2006; Bathiany et al. 2016a). Decreased ice thickness promotes amplification of a positive ice-albedo feedback, which can magnify sea ice anomalies (Perovich et al. 2007), and thin ice is more vulnerable to anomalous atmospheric forcing and oceanic transport due to the smaller amount of energy required to completely melt the ice (Maslanik et al. 1996, Zhao et al. 2018). For example, pulse-like increases in oceanic heat transport can trigger abrupt ice-loss events in sufficiently thin ice (Woodgate et al. 2012).

Changes in the interannual variability of sea ice have been studied only in a limited capacity, likely because they are only beginning to become visible in September in the present day. Both Goosse et al. (2009) and Swart et al. (2015; their Fig. S6) reported that maximum ice area variability during September occurs once the mean ice extent declines to 3-4 million km2. This increased variability may occur due to increased prevalence of RILEs and periods of rapid recovery during this timeframe (Döscher and Koenigk 2013). The thickness distribution during these periods skews toward thinner ice, which is conducive to both rapid ice loss and rapid recovery processes (Tietsche et al. 2011; Döscher and Koenigk 2013). Holland et al. (2008) considered a critical ice thickness that can serve as a precursor to RILEs, but found it more likely that intrinsic variability played the primary role in the particular RILEs that were studied. More recently, Massonet et al. (2018) analyzed the projected variability of sea ice *volume* and its projected future change in the CMIP5 ensemble, which suggests a monotonic future decrease. The corresponding variability of sea ice area was investigated by Olonscheck and Notz (2017), but their analysis was much coarser temporally and seasonally, in that it only compared changes between entire blocks of time (the historical 1850-2005 period vs. the future 2006-2100 interval) and was further restricted to the summer and winter seasons.

Building on these previous studies, our paper has two novel aspects. First, we analyze the transient interannual variability of sea ice area over the course of the year from the early 20th century through the entire 21st century and find very different behavior across the four seasons. These monthly differences are societally important, because marine access to the Arctic will likely expand beyond late summer as the ice pack shrinks. Second, we detail how interannual sea ice area variability changes as the ice pack retreats and link enhanced future variability to optimal ice thicknesses as well as the various thermodynamic and dynamic processes that control ice area variability. We analyze a large 40-member ensemble from a single GCM, which allows us to isolate internal variability, which is otherwise muddled with inter-model variability in multi-model comparisons. This allows us to test the hypothesis that inter-annual Arctic sea ice variability will increase throughout the year in the future as the ice pack diminishes.

**2. Data and Methods**

Ice thickness, concentration, and area were obtained from simulations of the Community Earth System Model Large Ensemble Project (CESM-LE). Ice concentration refers to the percentage of a given grid cell that is covered by ice, while ice area in this study refers specifically to this percent coverage multiplied by the area of the grid cell yielding a total Arctic ice-covered area. The CESM-LE was designed to enable an assessment of projected change in the climate system while incorporating a wide range of internal climate variability (Kay et al. 2015). It consists of 40 ensemble members simulating the period 1920-2100 under historical and projected (RCP8.5 emissions scenario only) external forcing. The ensemble members are produced by introducing a small, random round-off level difference in the initial air temperature field for each member. This then generates a consequent ensemble spread that is purely due to simulated internal climate variability. A full description of the CESM-LE is given in Kay et al. (2015), and similar ensembles using the weaker RCP4.5 and RCP2.6 scenarios can be found in Sanderson et al. (2017, 2018).

Another data set used in the current study is the model simulations from the Coupled Model Intercomparison Project Phase 5 (CMIP5). Although more than 40 models submitted their simulation results to the Program for Climate Model Diagnosis and Intercomparison (PCMDI), only 12 of them simulated the Arctic sea ice extent both of the monthly means (each individual month) and the magnitude of the seasonal cycle (March minus September sea-ice extent) within 20-percent error when compared with observations (Wang and Overland, 2012, Wang and Overland 2015). Therefore, we used only these 12 models identified by Wang and Overland (2015) in this study. The 12 models are: ACCESS1.0, ACCESS1.3, CCSM4, CESM1(CAM5.1), EC-EARTH, HadGEM2-AO, HadGEM2-CC, HadGEM2-ES, MIROC-ESM, MIROC-ESM-CHEM, MPI-ESM-LR, and MPI-ESM-MR. Among the 12 GCMs, half of them use the same sea ice model as CESM-LE (CICE) or a variation of it. If a GCM provided multiple ensemble members, we only kept up to 5 realizations, so that the total ensemble numbers is close to that used in CESM-LE. There are total 33 ensemble members from these 12 models in the RCP8.5 emissions scenario. Sea ice area, rather than ice extent, is computed from these 12 CMIP5 models to be consistent with CESM-LE results.

One of our primary analysis datasets is the time series of monthly ice variables. The ensemble mean of all statistics is taken after the statistics are calculated for each ensemble member. 1-year differences in ice area are calculated for each month separately to remove the confounding effect of amplified variability resulting from a downward trend. Finally, a 10-year running standard deviation is applied to the time series of 1-year differences in monthly ice area, centered on a given year. Ten years was chosen to quantify variability over decadal-scale intervals and to provide an adequate number of years for a standard deviation calculation. The timing and magnitude of variability is generally insensitive to the standard deviation window, however, and whether the 1-year difference in ice area or its raw time series is used.