# A Warming Greenland Ice Sheet: Temperature Uncertainties in Low (1.5 °C) and High (RCP 8.5) Warming Worlds

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Melting on the surface of the Greenland ice sheet has been changing dramatically as global air temperatures have increased in recent decades, including melt extent often exceeding the 1981-2010 median through much of the melt season and the onset of intermittent melt moving to earlier in the year. West Antarctica has also experienced recent unexpected melting events. To evaluate potential future change, we investigate surface melting drivers under both "low" (limited to 1.5 °C above pre-industrial global average temperature) and "high" (RCP 8.5) warming scenarios including analysis of differences in scenario outcomes. Analyses of melt-relevant variables are developed from two publicly available ensembles of CESM1-CAM5-BGC GCM runs: the 30-member Large Ensemble (CESM LE; Kay et al. 2015) for historical calibration and the RCP 8.5 scenario and the 11-member Low Warming ensemble (CESM LW; Sanderson et al. 2017) for the 1.5 °C scenario. For higher spatial resolution (15 km) and improved polar-centric model physics, we also apply the regional forecast model Polar WRF to decadal subsets (1996-2005; 2071-80) using GCM data archived at sub-daily resolution for boundary conditions. Models are skill-tested against ERA-Interim Reanalysis (ERAI) and observations from the GC-Net AWS network with a variety of metrics, including statistical distributions. These tests focused on the AWS with most complete records during comparison periods. With respect to daily average July surface temperatures (1996-2005), results for the CESM LE ensemble average include notable cold bias (Humboldt, Summit, Tunu-N, DYE-2, Saddle), warm bias (Crawford Point1, JAR1, NASA-E) and approximate alignment (Swiss Camp, NASA-SE). The ensemble average distribution is always much narrower than that of the observations. In most (7/10) cases, the distribution of all ensemble members approximates the range of observations but not always its shape. Based on a five-member ensemble, WRF does not fix all these issues but does broadly improve results including a broadening of the ensemble average distribution. As an extreme example, the ~5 °C CESM LE warm bias at JAR1 is essentially removed in the WRF results. As expected, Greenland does not escape future (2081-2100) warming (and expectations of more widespread surface melting) in the GCM predictions even in the LW scenario. But positive changes vs ERAI are mostly coastal (2-3 °C) with the interior showing only minor change. Under RCP 8.5, the entire ice sheet has warmed by 2-6 °C, or a median increase of ~5 °C vs LW. Adjusting for the CESM cold bias pushes these values closer to more frequent melting conditions. With respect to changes at AWS, WRF(LW) looks quite similar to WRF(LE historical) in the mean, i.e., the Low Warming scenario appears to maintain an approximate status quo in Greenland. The RCP8.5 scenario is less forgiving with AWS sites all warming in the mean, including a rise of ~5 °C at Summit. In summary, CESM LE shows a variety of skill issues both spatially and within different portions of the annual cycle. WRF driven by CESM LE improves but does not eliminate these issues. These results will be valuable towards developing robust uncertainty estimates for future surface melting predictions. Similar studies are anticipated to examine these questions in Antarctica.