

A Novel Model Hierarchy Isolates the Limited Effect of ~~Temperature-dependent Supercooled Liquid~~ Cloud Optics on Infrared Radiation

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Abstract. Clouds exert strong influences on surface energy budgets and climate projections. Yet, cloud physics is complex and often incompletely represented in models. For example, ~~temperature-dependent supercooled liquid~~ cloud optics parameterizations are rarely incorporated into the radiative transfer models used for ~~future~~-climate projections. Prior work has shown that incorporating these optics in ~~downwelling~~ longwave radiation calculations ~~results in increases of~~ increases Arctic downwelling longwave fluxes by as much as 1.7 W m^{-2} ~~for Arctic atmospheres~~. Here we examine whether implementing ~~these supercooled liquid water~~ optics in climate models ~~leads to significant climate impacts for longwave radiation impacts global radiative fluxes and climate~~. We use a novel methodology ~~based on that uses~~ a hierarchy of ~~models. In two-stream radiation and single-column models, incorporating temperature-dependent optical properties had a small impact (< 1 dynamical constraints on the sequence of atmospheric states. In the model experiments with stronger dynamical constraints, we find that the supercooled liquid water~~ optics increase Arctic downwelling longwave by $2.17\text{--}3.24 \text{ W m}^{-2}$). ~~Similarly, impacts were statistically insignificant on infrared radiation within freely evolving atmospheric model simulations.~~ In contrast, there was a much larger effect ($1\text{--}3$ ~~these optics increased Arctic downwelling longwave radiation by $0.36\text{--}0.68 \text{ W m}^{-2}$~~) ~~from optics changes when the winds within our atmospheric model experiments were nudged towards reanalysis winds. This new application of wind nudging experiments helped to isolate the effect from temperature-dependent cloud optics changes by reducing the internally generated atmospheric~~ variability with dynamically unconstrained model experiments. ~~While the optics impact was greater within the dynamically constrained models than in dynamically unconstrained models, the dynamically constrained models are also more idealized than the unconstrained models.~~ In summary, we found a signal from ~~temperature-dependent optics, but this effect is supercooled liquid water optics, the influence of these optics for longwave radiation are~~ small compared to ~~climate variability and didn't impact long-term Arctic temperature trends~~ the modeled longwave radiation variability. More broadly, this work demonstrates a ~~new novel~~ framework for assessing the climate importance of a physics change.

1 Introduction

Due to complex processes that couple cloud processes with the climate system, cloud radiative effects remain one of the largest sources of climate projection uncertainty (Webb et al., 2017; Sherwood et al., 2020). Clouds affect climate by absorbing and emitting longwave radiation and scattering shortwave radiation. The strength of these cloud radiative effects depends on the cloud properties, including the phase, particle size and number, and geometric thickness. For example, optically thick liquid clouds scatter more shortwave radiation and emit more longwave radiation than optically thin ice clouds. All else being equal, clouds with small particle sizes also scatter more shortwave (Maahn et al., 2021) and emit more downwelling longwave than clouds with large particle sizes (Lubin and Vogelmann, 2006).

In most climate models, translating cloud properties into cloud radiative impacts is accomplished through cloud optics parameterizations. Using an appropriate level of complexity in cloud optics parameterizations is therefore critical to accurately modeling cloud radiative impacts. Due to the computational expense of radiative transfer calculations, choices must be made about what aspects of cloud optics are incorporated. These choices should be re-assessed to include new physics when the impacts on radiation are substantial. Developing tools to assess whether a cloud optics change substantially affects model radiative fluxes is therefore of practical importance to the model development community.

A useful yet underutilized technique for isolating the importance of a cloud optics change for climate is wind nudging. In this technique, model winds are nudged towards prescribed wind values ~~-, often observed or reanalysis data, (often from reanalysis)~~ over a set horizontal and vertical domain. ~~The value of nudging the winds to the prescribed values~~ A key advantage of prescribing the winds using nudging is that the time evolution of the prescribed and modeled large-scale circulation is synchronized to the prescribed wind time evolution. Typically, winds are nudged above the boundary layer, leaving the boundary layer physics, including the surface fluxes and low clouds, to evolve interdependently. Recent applications show the power of wind nudging for scientific and direct model comparisons with observations. For example, Pithan et al. (2023) compared nudged model runs to observations ~~and made specific suggestions for to inform~~ model microphysical parameterization improvements in the Arctic. Likewise, Kooperman et al. (2012) leveraged the synchronizing of large-scale wind evolution enabled by wind nudging to increase the detectability of an aerosol radiative signal. These studies show that wind nudging is a powerful tool ~~for highlighting non-dynamical signals to amplify a radiative signal above chaotic atmospheric noise~~ by constraining the ~~atmospheric circulation in a climate model~~ time sequence of the modeled atmospheric circulation.

Based on these previous studies, what knowledge gaps does this study want to address? We identify a cloud optics physics that has not been incorporated into the radiation scheme used by many climate models, RRTMG (Iacono et al., 2008) (Clough et al., 2005; Iacono et al., 2008). Specifically, ~~temperature-dependent liquid water supercooled liquid water (240–273 K)~~ optics are not used in RRTMG. ~~Yet, using high-spectral-resolution models~~ Instead, RRTMG uses liquid water optics at one fixed temperature (298 K). Since the RRTMG optics temperature doesn't match supercooled liquid cloud temperatures, the RRTMG optics may not represent radiation emitted by supercooled liquid-containing clouds well. For instance, using a high spectral resolution line-by-line radiative transfer model applied to case studies in Antarctica the Arctic, Rowe et al. (2013) found that these optics can change supercooled liquid water optics can increase modeled longwave fluxes emitted by thin (liquid water path < 10 g m⁻²) super-

55 cooled liquid-containing clouds by up to 1.7 W m^{-2} . One limitation of the Rowe et al. (2013) study is that it only focused on a generalized Arctic case study. Here, we assess if using ~~temperature-dependent supercooled~~ liquid water optics for ~~downwelling longwave radiation in the Arctic longwave radiation~~ has substantial impacts on radiation ~~in a global climate context.~~ Thus globally and over many decades. Indeed, a primary goal of this study is to assess if this cloud optics change should be considered as a candidate for addition to the RRTMG radiative transfer model used by most climate models. ~~Our~~ 60 While our model simulations include optics changes at all latitudes, our assessment will focus on the Arctic, ~~where.~~ We focus on the Arctic because it is a cold and dry region where thin supercooled liquid clouds frequently occur in ~~both~~ observations (Cesana et al., 2012) and ~~the climate model we use (e.g. Community Earth System Model Version 2) (McIlhatten et al., 2020) and where the atmosphere is typically cold and dry, allowing significant infrared downwelling radiance from clouds to reach the surface (Rowe et al., 2013)~~ climate model simulations (McIlhatten et al., 2020). Thus, we anticipate the clouds optics change 65 may have a substantial impact on Arctic longwave fluxes.

A novel aspect of this study is using a hierarchy of models to assess the relevance of a this cloud optics change. ~~From simplest to most complex, these models are a two-stream radiative transfer model, a single-column atmospheric model, a freely evolving global climate model, and a wind-nudged global climate model. For each model, we then assess changes in longwave radiation produced by the temperature-dependent optics change that we make.~~ All models use the same radiation scheme (RRTMG), but 70 vary in the degree to which the atmosphere is dynamically constrained. We anticipate using this hierarchy of constraint on the modeled atmospheric circulation sequencing will be of value. We expect the most dynamically constrained models will enable the easiest detection of the optics change. In contrast, dynamically unconstrained models will have more noise from internal climate variability and that noise may make it hard to detect the optics change signal. While this study focuses on one specific cloud optics change, the ~~novel hierarchy and~~ methods used here are applicable to any ~~cloud optics model physics~~ change and 75 therefore should be of broad interest to the model development community. ~~Thus, a secondary goal is to establish the utility of this novel model hierarchy for assessing the importance of a physics parameterization change for the climate.~~

2 Methods

2.1 ~~Temperature-dependent~~ Supercooled liquid water optics

~~Our~~ The cloud optics change ~~is the implementation of temperature-dependent~~ we implement improves supercooled liquid water 80 optics relevant for supercooled liquid water. Supercooled liquid water (240–273 K) scatters and absorbs radiation differently than room temperature water ($\sim 298 \text{ K}$) (Rowe et al., 2020). ~~Rowe et al. (2013) focused on the consequences of including the temperature dependence of liquid cloud optics in two spectral regions where laboratory measurements are sufficiently accurate to determine the temperature dependence of refractive indices of supercooled liquid and where clouds have a strong impact on downwelling longwave radiation, in the dirty window (460–640) and in part of the atmospheric window (760–990~~ 85 ~~)~~. We define optics that account for this temperature dependence as "temperature-dependent" and optics that assume all water behaves the same as room temperature water as "temperature-independent". Figure 1 illustrates the difference in optics by plotting ~~temperature-dependent and temperature-independent~~ supercooled liquid water and room temperature water complex

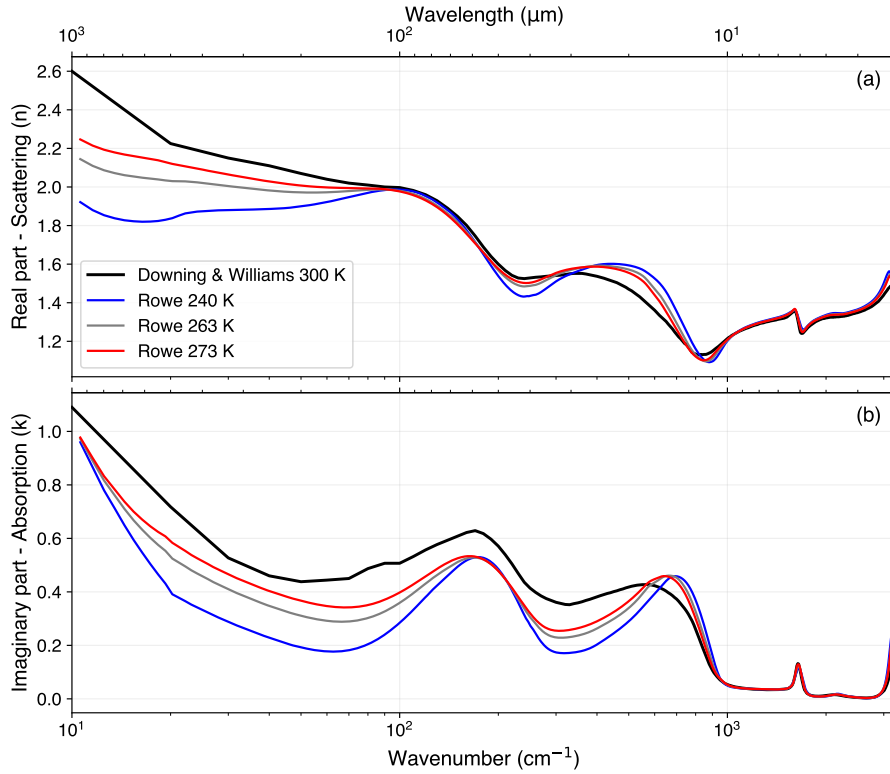


Figure 1. Complex refractive index of water with the (a) real part and (b) imaginary part between 10 and 3000 cm^{-1} for four complex refractive indices at different temperatures: 240 K, 263 K, and 273 K from Rowe et al. (2020) and 300 K from Downing and Williams (1975). The highlighted regions are the dirty (blue) and atmospheric (pink) windows.

refractive indices, which are defined as how a given material scatters and absorbs radiation as a function of wavelength. Optical properties used in our study were derived from these complex refractive indices. For the ~~temperature-dependent supercooled~~ liquid water optics, we used complex refractive indices from Rowe et al. (2020) at the temperatures of 240 K, 253 K, 263 K, and 273 K.

2.2 Model hierarchy

In this work, we evaluate the effect of changing the liquid water optics from ~~temperature-independent to temperature-dependent room temperature to supercooled~~ on longwave radiation at different scales. Therefore, we developed a model hierarchy with increasing complexity that includes four models: across a range of dynamically constrained models, while keeping the radiation scheme the same. The models in our hierarchy proceed from the most to least dynamically constrained atmosphere:

1. **Two-stream radiative transfer model:** a simplistic radiative transfer model that simulates the downwelling longwave spectra from a single supercooled liquid cloud. *Do we see an effect with a simple mathematical model on a spectral scale?*
- 100 2. **Single-column atmospheric model:** a single grid point version of a global atmospheric model constrained by observations for one month. *Do we see an effect with an atmospheric model at a single location on a daily time scale?* completely constrained model at a single location on a daily time scale
3. **Freely evolving Wind-nudged global climate model configurations:**
 - (a) Atmosphere-only (short time scale): a global dynamically constrained model on an annual time scale
 - 105 (b) Atmosphere-only (long time scale): a ~~climate model run over the entire globe for several decades. Do we see an effect with a global climate model over the entire Arctic on a decadal time scale?~~ global dynamically constrained model on a decadal time scale
 - (c) ~~Wind-nudged global climate model~~ Fully coupled (short time scale): a ~~climate model run over the entire globe for a single year and for several decades with the winds constrained to enhance the signal in the radiation. Do we see an effect with a dynamically constrained global climate model over the entire Arctic on annual and decadal time scales?~~ global fully coupled dynamically constrained model on an annual time scale
- 110 4. Freely evolving global climate model: an unconstrained global climate model on a decadal time scale

For each model, we compared the longwave radiation produced using ~~temperature-independent~~ room temperature water optics against longwave radiation produced using ~~temperature-dependent~~ supercooled liquid water optics. Then, we evaluated whether the difference in radiation was detectable and statistically significant. Finally, we assessed at what ~~scales and for which models the temperature dependence of time and spatial scales and degree of dynamical constraint the supercooled~~ liquid water optics mattered. Primarily, we focus on the downwelling longwave flux at the surface (W m^{-2}) to evaluate if the optics changed.

Diagram of the two-stream radiative transfer model as described in Petty (2006b). The gray layer represents the liquid cloud and the white layer the snow-covered ground. The cloud has a thickness Δz_{cld} . All quantities are functions of wavenumber. Quantities are color-coded by their emission source: red indicates original emission from the surface and blue from the cloud. F_{sfc} and F_{cld} represent the Planck black-body emissions of the snow surface and liquid cloud, respectively. ϵ_{cld} and t_{cld} represent the emissivity and transmissivity of the liquid cloud, respectively. The reflectivity or albedo of the ground and cloud are represented by r_{sfc} and r_{cld} , respectively.

2.3 Two-stream radiative transfer model

125 The first model in our hierarchy is a two-stream radiative transfer model following the work of Petty (2006b) and Rowe et al. (2013) (Fig. ??). We modeled a single liquid cloud with a droplet number concentration ($N = 40$) and an effective radius ($r_{\text{eff}} = 10$) based on observations of mixed-phase clouds from Klein et al. (2009). We used a non-black surface with an albedo ($r_{\text{sfc}} =$

0.2) and temperature ($T_{\text{sfc}} = 250$). For the temperature-dependent optics, we used the 240, 253, 263, and 273 optics from Rowe et al. (2020). For the temperature-independent optics, we used the 300 optics from Downing and Williams (1975). We
 130 calculated the Mie scattering properties (i.e. the asymmetry parameter, g ; the extinction efficiency Q_{ext} ; and the scattering efficiency, Q_{sca}) using the method outlined in Wiscombe (1979). The rest of the optical properties for the two-stream model we calculated using equations described in Petty (2006a)

2.3 RRTMG Liquid Water Optics

In order to use our supercooled liquid optics in RRTMG for all models in the hierarchy, we had to reproduce optics files in
 135 the same format as in RRTMG. The full list of equations we used in the two-stream model is included in Appendix ???. We modeled the downwelling longwave spectra from a single supercooled liquid cloud over the wavenumbers 770-1000. We also modeled the cloud with three different thicknesses (Δz_{clld} : 100, 500, and 1000) and four different temperatures (T_{clld} : description of how we created the optics files can be found in Appendix A. We produced optics files for 240 K, 253 K, 263 K, and 273 K). For each temperature, we calculated the spectra once using the temperature-dependent optics that matched
 140 the cloud temperature and once using the temperature-independent optics. The default liquid water optics file in RRTMG was based on 298 K water (room temperature) and we used these optics in all of our control experiments. RRTMG only uses the mass absorption coefficient (k_{abs}) in the longwave.

The longwave mass absorption coefficient (k_{abs}) graphed for the current CESM2 liquid optical properties (a) & (b) and for new liquid optical properties calculated from the 263 complex refractive index (Rowe et al., 2020) (c) & (d) as a function of
 145 wavenumber and wavelength. In CESM2, k_{abs} is a lookup table in terms of the parameters μ and $1/\lambda$ that describe the droplet size distribution where λ is a function of μ . (b) and (d) are the k_{abs} spectra at a fixed μ and five λ . (a) and (c) are the k_{abs} spectra at five μ and their corresponding λ .

2.4 Single-column atmospheric model

NextFirst, we evaluated the impact of temperature-dependent supercooled liquid water optics within a completely constrained
 150 single column model. Specifically, we used the Single-Column Atmospheric Model Version 6 (SCAM, Gettelman et al. (2019)), a well-documented simpler model available as part of the Community Earth System Model Version 2 (CESM2) (Danabasoglu et al., 2020). SCAM has all of the physics of parameterizations from the atmospheric component of CESM2, the Community Atmosphere Model Version 6 (CAM), but only runs including the radiation scheme RRTMG (Clough et al., 2005; Iacono et al., 2008). SCAM runs the CAM6 physics, including RRTMG, at a single location and prescribes the dynamics state (Gettelman et al., 2019).
 155 We forced SCAM all SCAM runs with 17 days of observations (temperature and aerosols) from the Mixed-Phase Arctic Cloud Experiment (MPACE) to simulate an Arctic atmosphere with mixed-phase and supercooled liquid-containing clouds (Harrington and Verlinde, 2005). In order to use our temperature-dependent optics in SCAM, we had to reproduce optics files in the same format as in SCAM/CESM2. The full description of how we created the optics files can be found in Appendix ???. We produced optics files for 240, 253, 263, and 273. The default For our supercooled liquid water optics file in CESM2 was based
 160 on 298 water and we used these optics in all of our control experiments. SCAM and CESM2 only use the mass absorption

Table 1. CESM2 experiments list

<u>Experiment name</u>	<u>Component configuration</u>	<u>Duration</u>	<u>Ensemble members</u>	<u>Optics sets</u>	<u>Wind nudging</u>
<u>F1850_UVnudge1980</u>	<u>Prognostic atmosphere & land, all other components prescribed</u>	<u>1 year</u>	<u>10</u>	<u>Control, 240 K, 263 K, 273K</u>	<u>67.5–82.5° N^a, above 820 hPa; U & V^b from ERA-I 1980</u>
<u>F1850_UVnudge1980–2018</u>	<u>Prognostic atmosphere & land, all other components prescribed</u>	<u>39 years</u>	<u>3</u>	<u>Control, 263 K</u>	<u>67.5–82.5° N, above 820 hPa; U & V from ERA-I 1980–2018</u>
<u>B1850_UVnudge1980</u>	<u>Fully coupled model (all components are prognostic)</u>	<u>1 year</u>	<u>10</u>	<u>Control, 263 K</u>	<u>67.5–82.5° N, above 820 hPa; U & V from ERA-I 1980</u>
<u>F1850</u>	<u>Prognostic atmosphere & land, all other components prescribed</u>	<u>40 years</u>	<u>1</u>	<u>Control, 240 K, 263 K, 273 K</u>	<u>–</u>

^aThe nudging window doesn’t cover the entire Arctic (60–90° N), but we conducted nudging window testing that shows little difference in the modeled radiation between the 67.5–82.5° N and the 60–90° N windows.

^bU & V are the zonal and meridional wind components, respectively.

coefficient (k_{abs}) in the longwave, which is plotted for the default optics and one of the temperature-dependent optics sets, 263, in Fig. A1. For our temperature-dependent optics experiments, experiments, we swapped the default file for one of our temperature-dependent supercooled liquid water optics files such that any liquid water in the atmosphere has those properties. To swap optics files, we gave SCAM the CAM namelist argument 'liopticsfile' the file path to a temperature-dependent supercooled liquid water optics file. We did this namelist change for all SCAM and CESM2 simulations where we used temperature-dependent optics supercooled liquid water optics optics. We ran SCAM forced by MPACE with four sets of optics: the control optics and the temperature-dependent supercooled liquid water 240 K, 263 K, and 273 K optics. We chose these optics sets to mirror the sets we used in the freely evolving and wind-nudged global climate model experiments. We used the downwelling longwave flux at the surface (–) to evaluate if the optics changed how much radiation the clouds emitted and absorbed. We used this variable for the rest of the model runs in CESM2.

2.5 Freely evolving global climate model

Next, we wanted to see the effect of temperature-dependent optics in a global climate on a large spatial scale and decadal temporal scale.

2.5 Wind-nudged global climate model

175 We used the Community Earth System Model Version 2.2 (CESM2) for all our global climate model runs (Danabasoglu et al., 2020). We selected this ~~climate~~-model because it is ~~a~~-widely used, well-documented, publicly available, and ~~observationally vetted climate models with~~ has vetted wind nudging capabilities (Kooperman et al., 2012). Previous work has analyzed and exposed important CESM2 Arctic biases, including an overestimation of cloud liquid (McIlhatten et al., 2020) and insufficient late summer Arctic sea ice cover (DuVivier et al., 2020). Understanding these known biases is valuable for the work here.

180 Notably, the overestimation of cloud liquid may amplify any effect of the ~~temperature-dependent supercooled liquid water~~ optics. In our model runs, we used a pre-industrial climate to examine the effect of ~~temperature-dependent supercooled liquid water~~ optics on the mean state of the Arctic climate. All simulations had a spatial resolution of $1^\circ \times 1^\circ$. ~~For the-~~

~~For our first set of experiments, we ran three 20 year simulations of CESM2 with prescribed sea ice and ocean surface where each run had a different set of optics: control, 240, and 273. We chose the 240 and 273 optics because these temperatures are the outer limits for supercooled liquid water. This group of experiments was called F1850 and is described in Table 1.~~

185 ~~CESM2 experiments list Experiment name Compset Duration Ensemble members Optics sets Wind nudging F1850 F1850^a 40 years 1 member Control, 240 experiments, 273 F1850_UVnudge1980 F1850 1 year 10 members Control, 240, 263, 273 67.5–82.5° N^c, above 820 ; U & V from ERA-I 1980 B1850_UVnudge1980 B1850^b 1 year 10 members Control, 263 67.5–82.5° N, above 820 ; U & V from ERA-I 1980 F1850_UVnudge1980–2018 F1850 39 years 3 members Control, 263 67.5–82.5° N, above 820 ; U & V from ERA-I 1980–2018~~

190 ~~67.5–82.5° N, above 820 ; U & V from ERA-I 1980–2018~~

2.6 ~~Wind-nudged global climate model~~

~~For our next set of experiments, we use~~ we used wind nudging, where the model uses a relaxation tendency term to nudge model values toward target values (Kooperman et al., 2012; Pithan et al., 2023). Nudging is implemented following:

$$\frac{dx}{dt} = F(x) + F_{\text{nudge}}, \quad (1)$$

195 $F_{\text{nudge}} = \alpha [O(t'_{\text{next}}) - x(t)] / \tau,$ (2)

where $F(x)$ the internal tendency without nudging, F_{nudge} is the nudging term, α is the strength coefficient that is 0 where nudging is not enabled and 1 where nudging is enabled, $O(t'_{\text{next}})$ is the ~~model state at a future target state at future target~~ time step, $x(t)$ is the model state at the current model time step, and τ is the relaxation time between the next target time step and the current model time step (Blanchard-Wrigglesworth et al., 2021; Roach and Blanchard-Wrigglesworth, 2022). In our

200 experiments, we nudged the horizontal wind components of CESM2 between 67.5–82.5° N and above 820 hPa (~~Fig. ??~~). At both the vertical and horizontal nudging boundaries, we applied smoothing. We nudged the model with 6-hourly ERA-Interim reanalysis (ERA-I) data (European Centre for Medium-Range Weather Forecasts, 2009). Nudging the winds constrains the internal variability of the modeled climate system to a specific sequence of atmospheric circulation, which was the ERA-I winds in our experiments. Since all experiments were constrained to the same atmospheric circulation sequence, they were all

205 likely to model the same sequence of clouds.

(a) Horizontal wind nudging window with nudging is on between 67.5–82.5° N. (b) Vertical wind nudging window with nudging is on above 820. Where wind nudging is enabled, the model nudges the horizontal wind components toward ERA-Interim reanalysis values.

All of our wind nudging experiments are detailed in Table 1. The first nudging experiment, called F1850_UVnudge1980,
210 was a 1 year 10 member ~~ensemble with prescribed sea ice and ocean and atmosphere-only ensemble with~~ the winds nudged
to 1980 values from ERA-I, ~~called F1850~~. ~~Nudging the winds constrains, but doesn't eliminate, the internal variability of.~~
Second, we assessed the long-term climate impacts of changing the optics by running another atmosphere-only experiment,
called F1850_UVnudge1980–2018, with 39 years of wind nudging. We ran three ensemble members to sample the modeled
~~climate system. Therefore, we ran this ensemble to quantify the internal variability of the wind-nudged climate system. We~~
215 ~~also model climate.~~ For this configuration, we nudged with ERA-I data from 1980–2018. We allowed the nudged winds to
evolve over time in the F1850_UVnudge1980–2018 experiments to evaluate the effect of the optics for a longer time span in a
dynamically constrained atmosphere. Finally, we ran the same 1 year 10 member wind-nudged ensemble with a fully coupled
model in a set of simulations called B1850_UVnudge1980. ~~We ran the~~ For this configuration, we also ran coupled simulations
to evaluate how adding ocean and sea ice feedbacks impacted the signal from the optics change. ~~Finally, we explored the~~
220 ~~long-term climate impacts of changing the optics by running a 39-year wind-nudged three-member ensemble with prescribed~~
~~sea ice and ocean. For this configuration, called F1850_UVnudge1980–2018, we nudged with ERA-I data from 1980–2018.~~
~~We allowed the nudged winds to evolve over time in the F1850_UVnudge1980–2018 experiments to evaluate how interannual~~
~~variability impacted the optics change.~~

We used several sets of ~~temperature-dependent~~ supercooled liquid water optics in our wind nudging experiments. For
225 the experiment F1850_UVnudge1980, we ran the configuration with the control optics and with the ~~temperature-dependent~~
supercooled liquid water 240 K, 263 K, and 273 K optics. We ~~continued with~~ chose the 240 K and 273 K optics ~~to evaluate the~~
~~outer bounds of the effect from the temperature-dependent optics because these temperatures are the outer limits for supercooled~~
liquid water. We also added the 263 K optics set because that temperature was the closest to the average CESM2 cloud tem-
perature in the Arctic. For the B1850_UVnudge1980 and F1850_UVnudge1980–2018 experiments, we ran both of these
230 configurations with the control optics and the ~~temperature-dependent~~ supercooled liquid water 263 K optics.

3 Results

(a) Downwelling irradiance spectra of a 240 supercooled liquid cloud ($\Delta z_{\text{clid}} = 100$) modeled using a two-stream radiative
transfer model between 770 and 1000. The spectra was modeled with both 240 optics (red) and 300 optics (black). (b) The
difference between the spectra modeled with 240 optics and 300 optics.

235 2.1 ~~Two-stream radiative transfer~~ Freely evolving global climate model

We start with the influence of temperature-dependent optics on radiation in our simplest model, the two-stream radiative transfer
model. As expected from Rowe et al. (2013), the downwelling irradiance and flux was higher for temperature-dependent optics

than temperature-independent optics. The thinnest clouds (100 thick with optical depth $\tau \sim 1-1.5$) showed the largest difference in downwelling flux between the temperature-dependent and temperature-independent optics (Fig. ??). For the 100 thick cloud, all cloud temperatures had a 0.35 flux difference between the temperature-dependent and temperature-independent optics. However, as cloud thickness increased from 100 to 500 ($\tau \sim 4-8$) and 1000 ($\tau \sim 10-15$) Lastly, we wanted to see the effect of supercooled liquid water optics in a dynamically unconstrained global climate on a large spatial scale and decadal temporal scale. For this set of experiments, we ran four 40 year-long atmosphere-only experiments, where each run had a different set of optics: control, 240 K, the difference caused by our cloud optics change was negligible. We also want to note that the effect in our spectral model was half the size that Rowe et al. (2013) found for comparable surface and cloud temperatures (0.66), but our model was meant to be a proof of concept and not realistic, like Rowe et al. (2013)'s 16+ stream spectral model 263 K, and 273 K (see F1850 experiments in Table 1). In all four simulations, the atmosphere evolves freely, as is the default in most global atmospheric and climate models.

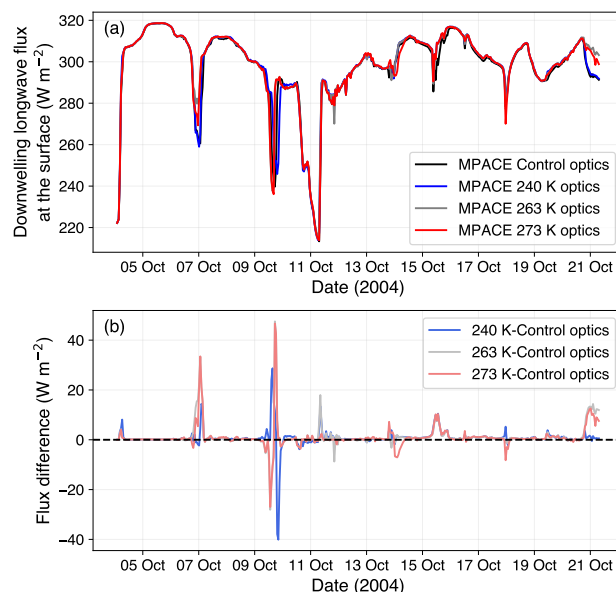


Figure 2. (a) Downwelling longwave flux at the surface modeled by SCAM for the MPACE IOP with four different sets of optics: Control - 298 K (black), 240 K (blue), 263 K (gray), and 273 K (red). (b) The difference in flux between the control and all three sets of temperature-dependent supercooled liquid water optics.

3 Results

250 3.1 Single-Column Atmospheric Model Arctic Case Study

NextFirst, we present results from the single-column atmospheric model runs for the Arctic field campaign MPACE held during October 2004. During almost the entire 17 day period, both ~~temperature-independent and temperature-dependent room temperature and supercooled liquid water~~ optics produced the same downwelling longwave flux at the surface (Fig. 2). The only notable differences (over 10 W m^{-2}) in downwelling longwave flux between the ~~temperature-dependent supercooled liquid water~~ optics and the control (~~temperature-independent room temperature water~~) optics simulations occurred on the dates of 7, 10, 11, and 21 October 2004. On these dates, there were differences in cloud fraction and dominant cloud phase between the ~~temperature-independent and temperature-dependent room temperature and supercooled liquid water optics~~ SCAM runs. Depending on these cloud type and amount disparities, flux differences were not consistently in one direction for all optics sets on a given date nor for one optics set over the entire model run. In summary, ~~cloud phase disparities the complex evolution of cloud phase~~ between SCAM runs complicated the attribution of differences in flux to changes in the cloud optics.

Table 2. Statistics from subsetted SCAM-MPACE downwelling longwave flux data

Optics set	Median (W m^{-2})	95 % confidence interval on median (W m^{-2})	Median _{optics set} - Median _{control optics} (W m^{-2})	Is the difference between medians statistically significant?
Control	307.09	(305.39, 308.18)	—	—
240 K	307.37	(306.19, 308.65)	0.28	No
263 K	307.57	(306.32, 308.54)	0.48	No
273 K	307.28	(305.84, 308.39)	0.21	No

Comparing downwelling longwave flux from ~~temperature-independent and temperature-dependent room temperature and supercooled liquid water~~ optics amongst all cloud types yielded unclear results ~~in the SCAM MPACE runs~~. Therefore, ~~to better isolate the signal~~, we focused our analysis of the cloud optics change on the cloud type where we anticipated the largest effect: ~~thin~~ supercooled liquid clouds. We isolated the impacts of the ~~temperature-dependent supercooled liquid water~~ optics by subsetting the downwelling longwave flux, only including data points when there were low-level supercooled liquid clouds and the atmosphere was optically thin ($\tau < 5$). Table 2 described the results of this sub-setting. Notably, the medians of all the subsetted ~~temperature-dependent supercooled optics~~ fluxes were larger than the subsetted ~~temperature-independent room temperature optics~~ fluxes by 0.21 to 0.48 W m^{-2} . ~~Although these flux differences were not large, they were similar to the flux differences we found in the two-stream radiative transfer model (Fig. ??).~~ This result showed that the downwelling flux modeled by SCAM for low-level supercooled liquid clouds was larger for the ~~temperature-dependent supercooled liquid water~~ optics. However, the differences between the ~~temperature-dependent and temperature-independent supercooled and room temperature~~ flux medians were not statistically significant at the 95 % ~~confidence~~ level (Table 2).

(a) The 40 year mean downwelling longwave flux at the surface from the F1850 control run. Flux differences in the 40 year averages between (b) the 240 and control optics runs and (c) the 273 and control optics runs from F1850. Stippling indicates

the differences are statistically significant at a 95 % level following Wilks (2016). The colormaps are generated based on work by Crameri et al. (2020).

3.2 Freely evolving global climate model

Having shown that the temperature-dependent optics produce slightly more longwave flux than temperature-independent optics in both a simplistic radiative transfer model and a single-column atmospheric model, we next describe results from a freely evolving atmosphere model run (F1850). For the F1850 experiment, the average downwelling longwave flux at the surface over the model run time span (40 years) was higher by $\sim 1\text{--}2$ over most of the Arctic for the temperature-dependent optics than the temperature-independent optics (Fig. 6). However, these flux differences were not statistically significant at a 95 % level. The small magnitude of the flux differences was outweighed by the large variability in the annual mean flux, making the flux differences statistically insignificant. We also observed that the total area where temperature-dependent optics produced more downwelling longwave flux was larger than where the temperature-independent optics produced more, but the spatial pattern of these areas was not consistent between Fig. 6b and Fig. 6c. This spatial inconsistency suggested, like the SCAM runs, that differences in the clouds between all three of the F1850 runs complicated our assessment of the impact on the flux from the temperature-dependent optics alone. In short, the SCAM MPACE experiments that were strongly dynamically constrained didn't show a significant effect from the supercooled liquid water optics.

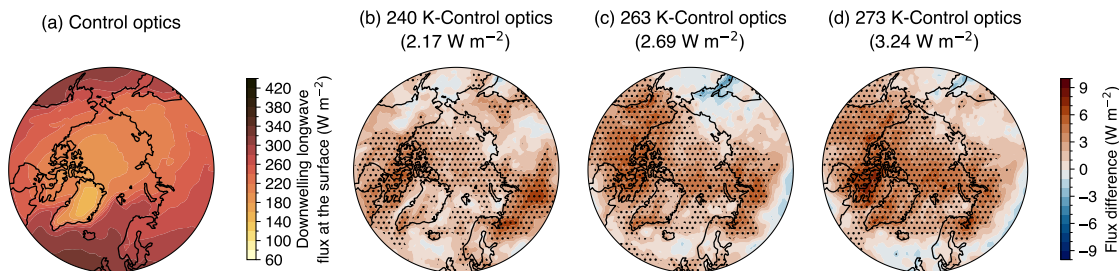


Figure 3. (a) The 1 year ensemble mean downwelling longwave flux at the surface from the F1850_UVnudge1980 control run. Flux differences in the 1 year ensemble averages between (b) the 240 K and control optics runs, (c) the 263 K and control optics runs, and (d) the 273 K and control optics runs from F1850_UVnudge1980. In parentheses above the (b), (c), and (d) plots is the spatial average of the flux differences over 60–90° N. Stippling indicates the differences are statistically significant at a the 95 % confidence level following . False discovery rate was controlled for using Wilks (2016). The colormaps are generated based on work by Crameri et al. (2020).

3.2 Wind-nudged global climate model

We next evaluate the impact of temperature-dependent supercooled liquid water optics on a wind-nudged atmosphere with an ensemble from the experiment F1850_UVnudge1980 (Table 1). The ensemble mean downwelling longwave flux at the surface from F1850_UVnudge1980 was higher ($\sim 1\text{--}7$ 2.17–3.24 W m⁻²) in most of the Arctic for the temperature-dependent

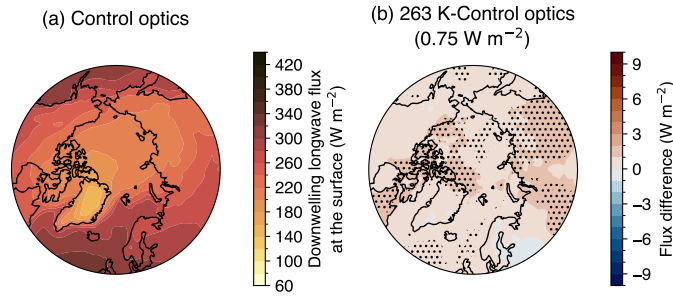


Figure 4. (a) The 39-year ensemble mean downwelling longwave flux at the surface from the B1850_F1850_UVnudge1980_UVnudge1980–2018 control run. Flux differences in the 39-year ensemble averages between (b) the 263 K and control optics runs from B1850_F1850_UVnudge1980_UVnudge1980–2018. In parentheses above the (b) plot is the spatial average of the flux differences over 60–90° N. Stippling indicates the differences are statistically significant at a 95 % confidence level following Wilks (2016). The colormaps are generated based on work by Crameri et al. (2020).

To understand the influence of ocean and sea ice coupling, we next describe the results from the coupled and dynamically constrained model ensemble (B1850_UVnudge1980). The ensemble mean of the downwelling longwave flux at the surface was higher ($\sim 1-3$) in some of the Arctic for the temperature-dependent optics (Fig. 5). Surprisingly, no flux differences due to the temperature-dependent optics were statistically significant. Although both B1850_UVnudge1980 and F1850_UVnudge1980 were nudged with the same winds, the nudging did not affect the variability in annual mean flux between ensemble members enough to make the flux differences significant.

These results demonstrated that enabling coupling to the ocean and sea ice model components reduced the effect of the temperature-dependent optics in spite of the wind nudging.

(a) The 39-year ensemble mean downwelling longwave flux at the surface from the F1850_UVnudge1980–2018 control run. Flux differences in the 39-year ensemble averages between (b) the 263 and control optics runs from F1850_UVnudge1980–2018. Stippling indicates the differences are statistically significant at a 95 % level following Wilks (2016). The colormaps are generated based on work by Crameri et al. (2020).

supercooled liquid water optics (Fig. 3). Critically, many flux differences were statistically significant, which showed that the temperature-dependent optics impacted longwave flux substantially in this modeling experiment at the 95 % confidence level. In other words, the influence of the supercooled liquid water optics change on longwave radiation was detectable. The flux differences became were statistically significant in this experiment because the wind nudging reduced the variability in the annual mean flux between the ensemble members. Additionally, the region of the Arctic where the temperature-dependent optics produced more downwelling longwave flux was much larger for the F1850_UVnudge1980 experiments and more consistent between the temperature-dependent optics sets than the F1850 experiments noise caused by different atmospheric circulation sequences and emphasized the signal from the supercooled liquid water optics. The spatial patterns of statistically significant flux differences for the F1850_UVnudge1980 experiments were also mostly consistent between the temperature-dependent supercooled liquid water optics sets. This high level of spatial consistency demonstrated that our results were not appreciably affected by wind nudging reduced atmospheric circulation differences between the model runs due to the wind nudging.

305 ~~Finally~~ Then, we detail the influence of ~~temperature-dependent supercooled liquid water~~ optics on a decadal time scale with a constrained atmosphere from our F1850_UVnudge1980–2018 experiment. The ensemble mean of the downwelling longwave flux at the surface was higher (~~~ 1.2~~ 0.75 W m^{-2}) in most of the Arctic for the ~~temperature-dependent supercooled liquid water~~ optics (Fig. 4). Some of these flux differences were statistically significant, ~~which showed that the temperature-dependent~~. Thus, the ~~supercooled liquid water~~ optics impacted longwave flux substantially on a decadal scale. However, the area and
310 magnitude of statistically significant flux differences in the F1850_UVnudge1980–2018 ensemble (Fig. 4b) were smaller than the F1850_UVnudge1980 ensemble (Fig. 3c). This decades-long ensemble had fewer ensemble members, and thus a smaller sample size of the model climate’s internal variability, and added interannual variability. In summary, the effect of the ~~temperature-dependent supercooled liquid water~~ optics was widespread across the Arctic and statistically significant in some places, but the magnitude of the effect on a decadal time was ~~only on the order of a few~~ $\text{less than one} \text{ W m}^{-2}$.

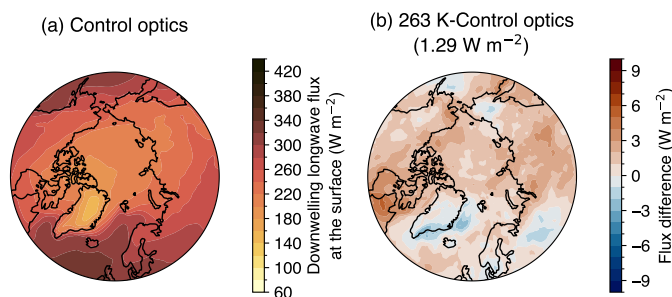


Figure 5. ~~Near-~~ (a) The 1 year ensemble mean downwelling longwave flux at the surface ~~annual-temperature-anomalies~~ from the F1850 ~~B1850_UVnudge1980–2018_UVnudge1980 control optics-run~~. Flux differences in the 1 year ensemble averages between (gray**b**) and the 263 K optics (blue) ensembles and control optics runs from B1850_UVnudge1980. Stippling indicates the ERA-I reanalysis (black) differences are statistically significant at the 95 % confidence level. False discovery rate was controlled for using Wilks (2016). The ~~temperature anomalies were averaged over 60–90° N~~ color maps are generated based on work by Crameri et al. (2020).

315 ~~Yet, this substantial impact on the~~ To understand the influence of ocean and sea ice coupling, we next describe the results from the coupled and dynamically constrained model ensemble (B1850_UVnudge1980). The ensemble mean of the downwelling longwave flux at the surface ~~for~~ was higher (1.29 W m^{-2}) in some of the Arctic for the supercooled liquid water optics (Fig. 5). Surprisingly, no flux differences due to the supercooled liquid water optics were statistically significant. These results demonstrated that enabling coupling to the ocean and sea ice model components reduced the ability to detect a radiation change
320 from the altered cloud optics in spite of the dynamical constraints.

3.3 Freely evolving global climate model

Having shown that the optics physics change produce slightly more downwelling surface longwave flux in dynamically constrained models, we last describe results from a freely evolving atmosphere model run with no dynamical constraints (F1850). This model run is the default configuration for almost all global atmospheric models. For the ~~decades-long ensemble~~

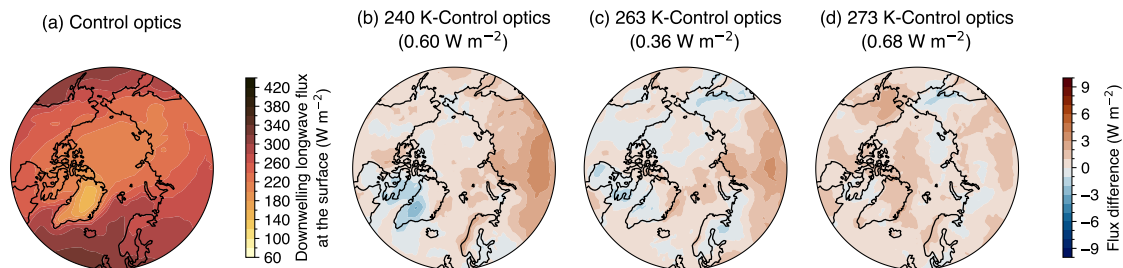


Figure 6. (a) The 40 year mean downwelling longwave flux at the surface from the F1850 control run. Flux differences in the 40 year averages between (b) the 240 K and control optics runs, (c) the 263 K and control optics runs, and (d) the 273 K and control optics runs from F1850_UVnudge1980. In parentheses above the (b), (c), and (d) plots is the spatial average of the flux differences over 60–90° N. Stippling indicates the differences are statistically significant at the 95 % confidence level. False discovery rate was controlled for using Wilks (2016). The colormaps are generated based on work by Cramer et al. (2020).

325 did not translate into an effect on surface temperature. Figure ?? shows Arctic near surface temperature anomalies for the F1850_UVnudge1980–2018 ensembles and the ERA-I data. The temperature trends for the control (–0.008 to 0.030) and 263 (–0.0019 to –0.004) experiment, the average downwelling longwave flux at the surface over the model run time span (40 years) was higher by 0.36–0.68 W m^{-2} over most of the Arctic for the supercooled liquid water optics than the room temperature water optics (Fig. 6). Globally, the supercooled liquid water optics increased the downwelling longwave flux by 0.20–0.27 W m^{-2} . However, all these flux differences were not statistically significant at the 95 % confidence level. We also observed that the total area where supercooled liquid water optics produced more downwelling longwave flux was larger than where the room temperature water optics produced more, but the spatial pattern of these areas was not consistent between Fig. 6b and Fig. 6c. This spatial inconsistency suggests that differences due to internal climate variability between all three of the F1850_UVnudge1980–2018 ensembles remained near zero and were minuscule compared to the ERA-I trend (0.650) runs.

335 complicated our ability to detect the signal from the supercooled liquid water optics alone over the chaotic atmospheric noise.

Although the results thus far focus on downwelling surface longwave radiation, the supercooled liquid water optics that we implemented impact longwave radiation emitted in all directions. Of critical importance, outgoing longwave radiation emitted at the top of the atmosphere (OLR) contributes to the planetary energy balance. Thus, we also assessed the optics impact on

340 OLR from the freely evolving climate model run. We found the globally averaged OLR changes resulting from the optics changes are small (0.08–0.11 W m^{-2}) and not statistically significant. Thus, this short analysis of the OLR provides additional evidence that the influence of the optics change on the freely evolving model is modest.

4 Discussion

Our main conclusion is that ~~temperature-dependent optics are not a first priority for climate model radiation parameterization development~~the effect of including supercooled liquid water optics is small but non-negligible. While the optics did have a ~~substantial~~an impact on the mean state Arctic longwave radiation at range of ~~model temporal and spatial scales~~atmospheric dynamical constraints, their effect in the model ~~experiment~~experiments closest to the real world and to a typical unconstrained model, the wind-nudged coupled ensemble and freely-evolving model run, the coupled ensemble, was minimal and statistically insignificant. We found that the effect of the ~~temperature-dependent optics was about 1–3~~supercooled liquid water optics was 0.36–3.24 W m^{-2} , which confirmed the results from Rowe et al. (2013) case study. Our novel model hierarchy worked, taking new physics and case study results and finding a similar size effect on the climate. However, an effect of this magnitude has different implications when considering a case study versus a global climate model. In the case study results from Rowe et al. (2013, 2022), they concluded that the ~~1–2~~1.7 W m^{-2} effect of these optics mattered when retrieving cloud properties from radiance measurements because retrievals of ice and liquid effective radii, ice fraction, and liquid water path were affected substantially. Whereas for the global climate model, an effect of a few W m^{-2} is within climate variability and thus relatively small. ~~Additionally, the optics didn't affect surface temperature trends in the decade-long wind-nudged ensemble.~~ However, the effect of these optics was not negligible and we recommend that model development add these optics to the list of parameterizations to be added RRTMG.

~~Process for detecting and evaluating the significance of a physics change in a model hierarchy of a conceptual model, single-column model, climate model, and wind-nudged climate model.~~

This study has additional value in showing how a model hierarchy can be used to assess the importance of a model physics change. In the first step, the ~~two-stream radiative transfer model showed us that the optics change had an effect in a mathematical model (Fig. ??, panel 1), grounding evidence of our effect in the principles of radiative transfer. Second, the single-column model showed us the effect in a fully~~ parameterized-constrained atmospheric model at a single location (Fig. ??, panel 2). We found it ~~harder~~hard to isolate the effect of the optics in this model ~~and it was at this level of model complexity we began to suspect that the physics change might not produce a substantial effect~~because of the short, daily, time scale. We also realized that internal variability and dynamical differences related to clouds between model runs might affect our results. The wind nudging step in the hierarchy allowed us to constrain the ~~dynamic variability~~atmospheric dynamics and amplify the signal in the radiation from the optics change ~~. In the third step~~relative to the noise. Lastly, we evaluated the optics change in an freely evolving global climate and found a statistically insignificant impact (Fig. ??, panel 3). The results at this step confirmed our earlier suspicions that ~~dynamics would~~unconstrained dynamics might obscure our ability to isolate the effect of the optics. The novel addition of wind nudging in ~~the final step of~~ this hierarchy allowed us to constrain the dynamic variability and amplify the signal in the radiation from the optics change to a ~~statistically significant level~~(Fig. ??, panel 4). substantial level. This hierarchy taught us a lot about the impact of our physics change because it told us at what ~~model complexity degree~~of dynamical constraint and time and spatial scales the optics had an effect, as summarized in Table 3. As a result, this novel

Table 3. Summary of the effect of ~~temperature-dependent supercooled liquid water~~ optics over the entire model hierarchy. The effect of the optics for F1850_UVnudge1980, F1850_UVnudge1980–2018, B1850_UVnudge1980, and F1850 is the regional average over the spatial scale. A range of values in the effect of the optics represents the minimum and maximum effect from multiple optics sets.

Experiment name	Model complexity & dynamical constraint	Spatial scale	Time scale	Ensemble members	Effect of optics	Substantial?
Two-stream-radiative transfer model-Simple mathematical model-----0.35-NoSCAM	Full-Completely constrained atmospheric model	One grid cell	Days (17)	–	0.21–0.48 W m ^{–2}	No
F1850_UVnudge1980	Global-Dynamically constrained global climate model with prescribed ocean and sea ice	Entire Arctic (50–90°60–90° N)	Decades (4Year (1)	–10	1–32.17–3.24 W m ^{–2}	NoYes
F1850_UVnudge1980 UVnudge1980–2018	Global-Dynamically constrained global climate model with prescribed ocean and sea ice and nudged winds-	Entire Arctic (50–90°60–90° N)	Year (4Decades (4)	10-3	1-70.75 W m ^{–2}	Yes
B1850_UVnudge1980	Fully coupled & dynamically constrained global climate model with nudged winds-	Entire Arctic (50–90°60–90° N)	Year (1)	10	1-31.29 W m ^{–2}	No
F1850 _UVnudge1980–2018-	Global-Unconstrained global climate model with prescribed ocean and sea ice and nudged winds-	Entire Arctic (50–90°60–90° N)	Decades (4)	3~	1-20.36–0.68 W m ^{–2}	YesNo

model hierarchy enabled us to make specific conclusions about the effect of the optics and recommendations to the model development community.

There are some limitations and caveats of our study that we want to address. First, it is important to note that large uncertainties remain in the ~~temperature-dependent supercooled liquid water~~ optics in climatologically important spectral regions, including below 500 cm^{-1} and from 1075 to 1575 cm^{-1} , ~~where the temperature dependence is unknown~~ (Rowe et al., 2020). Second, CESM2 CAM6 is known to have optically thick mean state Arctic clouds (McIlhatten et al., 2020) and we know from the case study results (Rowe et al., 2013) that the effect of the ~~temperature-dependent supercooled liquid water~~ optics is greatest for clouds with liquid water paths of 1 to 10 g m^{-2} , which are optically thin. From this perspective, our study may be underestimating the effect of these optics. To address this, we could re-run steps ~~three and four~~ two and three of our model hierarchy in a model with mean state optically thinner clouds, such as CESM2 CAM5 (McIlhatten et al., 2017). Yet, models like CAM5 with these thinner clouds underestimate supercooled liquid and overestimate ice in Arctic clouds (Kay et al., 2016). Considering these competing biases and the fact that CAM6's supercooled liquid is more realistic than CAM5's (Gettelman et al., 2020; McIlhatten et al., 2020), ~~we justify our choice to use CESM2 CAM6 in our model hierarchy~~ is a reasonable choice for this study. However, our model evaluation was based on performance in the Arctic and with respect to supercooled liquid. Scientists utilizing this hierarchy outside of the Arctic need to consider biases appropriate for their spatial domain and variables when choosing the global climate model for ~~hierarchy steps three and four~~ the hierarchy. Third, our conclusions about the impact of ~~temperature-dependent supercooled liquid water~~ optics are limited to the models we used. We recommend using our model hierarchy structure to test the effect of these optics in other climate models. For high resolution spectral radiation models, we recommend consulting Rowe et al. (2013) because they use a comparable model. Finally, ~~the computational cost of fully implementing the temperature-dependent optics would be immense~~ supercooled liquid water optics would increase the model computational cost. In our study, we switched out the liquid optics lookup table, which didn't change the computational cost. Ideally, the model would match the cloud temperature and optics temperature by interpolating the optics properties. This implementation would ~~mean involve~~ the model performing that interpolation at every timestep and grid cell, increasing the cost of the already costly radiation scheme significantly. One possible compromise to these two implementation approaches would be ~~to~~ to find the optics set closest to the cloud temperature and use that lookup table. We expect this third approach would be easy to implement and nominally increase the radiation scheme's computational cost.

Based on our study results, we have some suggestions for future work regarding both the ~~temperature-dependent supercooled liquid water~~ optics and the model hierarchy. First, the Antarctic and Southern Ocean have a high occurrence of supercooled liquid (Gettelman et al., 2020), including optically thin supercooled liquid clouds ~~at 240~~ (Rowe et al., 2022). In addition, the atmosphere of the Antarctic interior is colder and drier than the Arctic, and there is evidence that liquid effective radii are smaller in the ~~Arctic~~ Antarctic (Lubin et al., 2020), which ~~would cause the temperature-dependent~~ could cause the supercooled liquid water optics to have ~~a~~ an even larger effect (Rowe et al., 2013). These factors make the Antarctic a prime second location to test the effect of the ~~temperature-dependent supercooled liquid water~~ optics, specifically the wind-nudging experiments from the model hierarchy. Furthermore, the effect of the ~~temperature-dependent supercooled liquid water~~ optics is also of import for upwelling infrared radiation, which is expected to have a magnitude about twice as large in the tropics as the effect on downwelling infrared radiation in the Arctic for a supercooled liquid cloud at 240 K and typical atmospheres (Rowe et al., 2013). While assessing the Antarctic and the tropical influence of these optics changes would be of regional interest, we want

to emphasize that this work found that both the global and Arctic mean impacts on longwave radiation were often modest not statistically significant. Another avenue for future research is using our novel model hierarchy to evaluate the impact of other potential model physics additions. For example, Meng et al. (2022) developed a new dust particle size distribution for CESM that improved the representation of super coarse dust. However, their work didn't assess the new dust parameterization outside of the dust size distribution and our model hierarchy could be used to evaluate this parameterization's impact on cloud properties, aerosol optical depth, aerosol radiative forcing, etc. before it is incorporated into CESM. Taking a step back from individual parameterizations, this model hierarchy could even be used to detect changes between different versions of radiation or microphysical schemes.

5 Conclusions

In this study, we assessed the impact of ~~temperature-dependent supercooled~~ liquid water optics on longwave radiation in the Arctic over a hierarchy of models. Our model hierarchy, ~~increasing in complexity decreasing in degree of dynamical constraint~~, included a ~~mathematical two-stream radiative transfer model~~, a single-column atmospheric model, a ~~freely evolving several~~ wind-nudged global climate model configurations, and a ~~wind-nudged freely evolving~~ global climate model. We found that the optics had insubstantial effects ~~on the order of 0.1 at 0.21–0.48~~ W m^{-2} for both the two-stream and the single-column models. For the freely evolving global climate model (CESM2), the optics had a 1–3 effect on a decadal time scale that we deemed insubstantial because of high interannual variability within the model ~~model Arctic case study~~. In the wind-nudged model ensemble at a year-long time scale, the optics had a substantial ~~1–7 2.17–3.24~~ W m^{-2} effect in the Arctic for an atmosphere-only configuration and an insubstantial 1–3 effect in a coupled configuration. This result demonstrated. Extending the wind-nudged ensemble's length to 39 years reduced the effect of the optics to a still substantial 0.75 W m^{-2} . Yet, the wind-nudged fully coupled year-long ensemble found an insubstantial optics effect of 1.29 W m^{-2} . These results demonstrate that constraining the dynamic variability through wind-nudging amplified the non-dynamical signal of the ~~temperature-dependent supercooled liquid water~~ optics, but adding coupled ocean and sea ice components to the model and making it more realistic, reduced the impact of the optics significantly. Finally, ~~with a wind-nudged atmosphere-only ensemble on a decadal scale, we found that for the freely evolving global climate model (CESM2), the optics had a substantial 1–2 0.36–0.68~~ W m^{-2} effect in the Arctic on a decadal time scale that we deemed insubstantial because of the atmospheric noise within the model. Our first conclusion is that given the magnitude of the optics' effect on longwave radiation at various ~~model, time, degrees of dynamical constraint and time~~ and spatial scales, the ~~temperature-dependent supercooled liquid water~~ optics should eventually be added to radiation parameterizations, but that they are not a first priority. Our second conclusion is that the model hierarchy we developed can be used to assess the importance of model physics changes, such as new parameterizations or entire schemes.

Appendix A: ~~Equations~~ RRTMG optics calculation

A1 Two-stream radiative transfer model

We used a gamma distribution to represent the droplet size distribution as a function of the droplet radius ($n(r)$). The distribution of radii covered 0.01 to 50 with an increment of 1. The following equations described the properties of the gamma distribution as outlined in Petty (2006a):-

$$\begin{aligned} \alpha &= 3, \\ n(r) &= ar^\alpha e^{-br}, \\ b &= \frac{\alpha + 3}{r_{\text{eff}}}, \\ a &= \frac{Nb^{\alpha+1}}{\alpha!}, \end{aligned}$$

where α , a , and b were the parameters that describe the gamma distribution. The extinction efficiency (Q_{ext}) and scattering efficiency (Q_{sca}) were calculated as functions of wavenumber ($\tilde{\nu}$) and droplet radius (r) using the method in Wiscombe (1979). We used the wavenumbers 770 to 1000 with an increment of 1. We calculated the volume extinction coefficient (β_{ext}) and the single-scattering albedo ($\tilde{\omega}$) solely as functions of wavenumber with the following equations from Petty (2006a):-

$$\begin{aligned} \beta_{\text{ext}} &= \int_0^r n(r) Q_{\text{ext}}(r) \pi r^2 dr, \\ \tilde{\omega} &= \frac{1}{N} \int_0^r n(r) \frac{Q_{\text{sca}}(r)}{Q_{\text{ext}}(r)} dr. \end{aligned}$$

Then, we took β_{ext} and $\tilde{\omega}$ and calculated the following quantities for the two-stream radiative transfer model as functions of wavenumber from Petty (2006b):-

$$\begin{aligned} \tau^* &= \beta_{\text{ext}} \Delta z_{\text{cld}}, \\ \Gamma &= 2\sqrt{1 - \tilde{\omega}} \sqrt{1 - g\tilde{\omega}}, \\ r_\infty &= \frac{\sqrt{1 - g\tilde{\omega}} - \sqrt{1 - \tilde{\omega}}}{\sqrt{1 - g\tilde{\omega}} + \sqrt{1 - \tilde{\omega}}}, \\ r &= \frac{r_\infty [e^{\Gamma\tau^*} - e^{-\Gamma\tau^*}]}{e^{\Gamma\tau^*} - r_\infty^2 e^{-\Gamma\tau^*}}, \\ t &= \frac{1 - r_\infty^2}{e^{\Gamma\tau^*} - r_\infty^2 e^{-\Gamma\tau^*}}, \end{aligned}$$

where Δz_{cld} was the cloud thickness, τ^* was the cloud optical depth, Γ was a parameter, r_∞ was the albedo of a semi-infinite cloud, and r and t were the cloud reflectance and transmittance over a black surface, respectively. Since we

assumed in our two-stream model used a snow surface, we calculated the following quantities as functions of wavenumber to find the cloud properties over a non-black surface from Petty (2006b):-

$$\tilde{r} = \frac{r + r_{\text{sfc}} t^2}{1 - r_{\text{sfc}} r},$$

$$\tilde{t} = \frac{t}{1 - r_{\text{sfc}} r},$$

$$\varepsilon = 1 - \tilde{r} - \tilde{t},$$

where $\tilde{r}$, $\tilde{t}$, and ε were the cloud reflectance, transmittance, and emissivity over a non-black surface, respectively, and r_{sfc} was the surface albedo. We also assumed that emissivity was equal to absorptivity according to Kirchhoff's Law. Finally we calculated the downwelling longwave spectra ($F_{\downarrow, \tilde{\nu}}$) as a function of wavenumber and the flux ($F_{\downarrow}$) for the cloud at the surface with the following equations from Petty (2006b):-

$$F_{\downarrow, \tilde{\nu}} = \tilde{r}_{\tilde{\nu}} B_{\tilde{\nu}}(T_{\text{sfc}})(1 - r_{\text{sfc}}) + \varepsilon_{\tilde{\nu}} B_{\tilde{\nu}}(T_{\text{cld}}),$$

$$F_{\downarrow}(\tilde{\nu}_1, \tilde{\nu}_2) = \int_{\tilde{\nu}_1}^{\tilde{\nu}_2} F_{\downarrow, \tilde{\nu}} d\tilde{\nu},$$

where $B_{\tilde{\nu}}(T)$ was the Planck blackbody function and T_{sfc} and T_{cld} were the temperatures of the surface and cloud, respectively.

A1 CESM2 optics calculation

The ~~CESM2 radiation scheme~~ RRTMG radiation scheme in CESM2 and SCAM has 16 longwave bands and 14 shortwave bands, as shown in Tables ~~?? and ??~~ A1 and A2, respectively. The optics file contains the following variables for both longwave and shortwave bands: mass extinction coefficient (k_{ext}), mass absorption coefficient (k_{abs}), mass scattering coefficient (k_{sca}), single-scattering albedo ($\tilde{\omega}$), asymmetry parameter (g), extinction efficiency (Q_{ext}), absorption efficiency (Q_{abs}), and scattering efficiency (Q_{sca}). Each variable has the dimensions μ and λ . These parameters describe the gamma distribution that defined

Table A1. RRTMG longwave bands

Band index	Band minimum (μm)	Band maximum (μm)	Band midpoint (μm)	Band minimum (cm ⁻¹)	Band maximum (cm ⁻¹)	Band midpoint (cm ⁻¹)
1	28.57	1000.0	169.03	10	350	59
2	20.00	28.57	23.90	350	500	418
3	15.87	20.0	17.82	500	630	561
4	14.29	15.87	15.06	630	700	664
5	12.20	14.29	13.20	700	820	758
6	10.20	12.20	11.16	820	980	896
7	9.26	10.20	9.72	980	1080	1029
8	8.47	9.26	8.86	1080	1180	1129
9	7.19	8.47	7.81	1180	1390	1281
10	6.76	7.19	6.97	1390	1480	1434
11	5.56	6.76	6.13	1480	1800	1632
12	4.81	5.56	5.17	1800	2080	1935
13	4.44	4.81	4.62	2080	2250	2163
14	4.20	4.44	4.31	2250	2380	2319
15	3.85	4.20	4.01	2380	2600	2493
16	3.08	3.85	3.44	2600	3250	2907

485 the droplet size distribution ($n(D)$) as a function of droplet diameter in the following equations:

$$2 < \mu < 15, \quad (A1)$$

$$\frac{\mu + 1}{50 \times 10^{-6} \text{ m}} < \lambda < \frac{\mu + 1}{2 \times 10^{-6} \text{ m}}, \quad (A2)$$

$$n(D) = \frac{\lambda^{\mu+1}}{\Gamma(\mu+1)} D^{\mu} e^{-\lambda D}, \quad (A3)$$

$$N = \frac{\Gamma(\mu+1)}{\lambda^{\mu+1}}, \quad (A4)$$

490 $D_{\text{eff}} = \frac{\mu + 3}{\lambda}, \quad (A5)$

$$x = \frac{\pi D_{\text{eff}}}{\lambda}, \quad (A6)$$

where N was the droplet number concentration, D_{eff} was the effective droplet diameter, and x was the size parameter. For equation A6, λ represented wavelength, but for equations A1-A5, λ was the droplet size distribution parameter.

495 We calculated Q_{ext} , Q_{sca} , and g as functions of wavenumber with the method outlined in Wiscombe (1979). For the rest

Table A2. RRTMG shortwave bands

Band index	Band minimum (μm)	Band maximum (μm)	Band midpoint (μm)	Band minimum (cm ⁻¹)	Band maximum (cm ⁻¹)	Band midpoint (cm ⁻¹)
1	3.077	3.846	3.440	2600	3250	2907
2	2.500	3.077	2.773	3250	4000	3606
3	2.150	2.500	2.319	4000	4650	4313
4	1.942	2.150	2.043	4650	5150	4894
5	1.626	1.942	1.777	5150	6150	5628
6	1.299	1.626	1.453	6150	7700	6881
7	1.242	1.299	1.270	7700	8050	7873
8	0.778	1.242	0.983	8050	12850	10171
9	0.625	0.778	0.697	12850	16000	14339
10	0.442	0.625	0.525	16000	22650	19037
11	0.345	0.442	0.390	22650	29000	25629
12	0.263	0.345	0.301	29000	38000	33196
13	0.200	0.263	0.229	38000	50000	43589
14	3.846	12.195	6.849	820	2600	1460

of the variables in the file, we used the following equations:

$$Q_{\text{abs}} = Q_{\text{ext}} - Q_{\text{sca}}, \quad (\text{A7})$$

$$\tilde{\omega} = \frac{Q_{\text{sca}}}{Q_{\text{ext}}}, \quad (\text{A8})$$

$$k_{\text{abs}} = \frac{3Q_{\text{abs}}\lambda}{2\rho_w(\mu + 3)}, \quad (\text{A9})$$

$$k_{\text{ext}} = \frac{3Q_{\text{ext}}\lambda}{2\rho_w(\mu + 3)}, \quad (\text{A10})$$

$$k_{\text{sca}} = \frac{3Q_{\text{sca}}\lambda}{2\rho_w(\mu + 3)}, \quad (\text{A11})$$

where λ and μ were the parameters for the droplet size distribution and ρ_w was the density of water. For each longwave and shortwave band, we calculated each variable at the band maximum, midpoint, and minimum. Then, we took the average of those three values and saved that average value to the optics file for that band. [In Fig. A1, an example of the new \$k_{\text{abs}}\$ for the](#)

[263 K optics is contrasted against the default RRTMG optics at 298 K.](#)

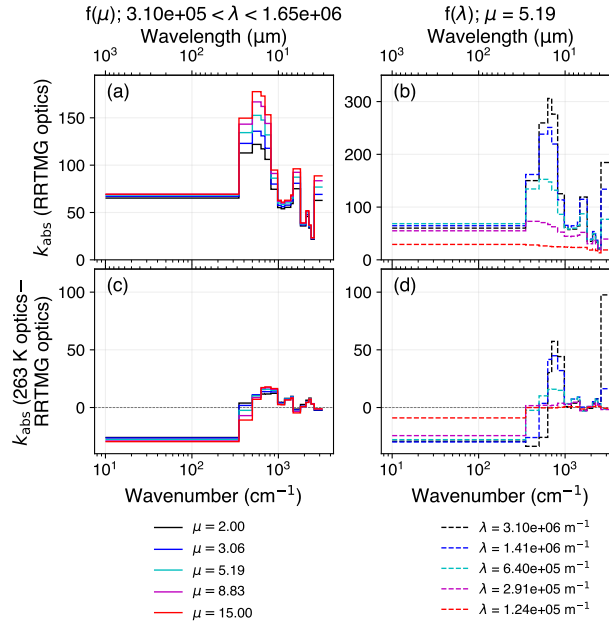


Figure A1. The longwave mass absorption coefficient (k_{abs} ($\text{m}^2 \text{kg}^{-1}$)) graphed for the current RRTMG liquid optical properties (a) & (b) as function of wavenumber and wavelength. The difference in longwave mass absorption coefficient between new liquid optical properties calculated from the 263 K complex refractive index (Rowe et al., 2020) and the current RRTMG liquid optical properties (c) & (d) is also graphed as a function of wavenumber and wavelength. In RRTMG, k_{abs} is a lookup table in terms of the parameters μ and $1/\lambda$ that describe the droplet size distribution where λ is a function of μ . (b) and (d) are the k_{abs} spectra at a fixed μ and five λ . (a) and (c) are the k_{abs} spectra at five μ and their corresponding λ .

Code and data availability. The supercooled liquid water CRI and optics and the processed SCAM and CESM2 data are available from <https://doi.org/10.5281/zenodo.15741756> (Gilbert, 2025a). The code needed to run all of the model hierarchy experiments and the namelists for the SCAM and CESM2 experiments are available from <https://doi.org/10.5281/zenodo.15741919> (Gilbert, 2025b).

Author contributions. AG and JEK designed the experiments and model hierarchy. AG performed the model runs and analysis. JEK and PR provided input on the analysis. AG wrote the paper, with input from all authors.

Competing interests. The authors declare that they have no conflict of interest.

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