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Comment on "On the reliability of simulated Arctic sea ice in global climate models" by I. Eisenman, N. Untersteiner, and J. S. Wettlaufer

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[1] *Eisenman et al.* [2007] (hereinafter referred to as EUW) consider the uncertainty in simulations of Arctic sea ice thickness owing to uncertainties in the simulation of the surface energy fluxes over sea ice. They raise the possibility that coupled climate models may be "tuned" to simulate present-day ice conditions in ways that mask severe deficiencies in model physics. In that case, a successful present-day sea ice simulation would lend false credibility to simulations of future sea ice decline performed with that model. They identify sea ice albedo as an ideal "tuning knob" and argue that minute changes in albedo would be sufficient to adjust sea ice thickness to compensate otherwise egregious errors due to poor simulation of Arctic clouds. In an ensemble of 20th century climate model simulations, they argue that albedo adjustments within ±0.10 would be sufficient to reduce the ensemble spread of sea ice thickness from over 10 m (the range based on theoretical arguments) to the 3 m range found in the model output.

[2] Our experience with the National Center for Atmospheric Research (NCAR) Community Climate System Model (CCSM3) is not consistent with the authors' claim that ice thickness can be arbitrarily adjusted through precision tuning of albedo. *Holland et al.* [2006] present results from a model integration in which an albedo increase of 0.13 yields a central Arctic ice thickness increase from 1.95 m to 2.5 m. Because the snow and open water albedo are largely unchanged, the imposed 0.13 albedo increase results in an 0.08 actual increase in MJJA surface albedo (Table 1), a change which would increase thickness from 2 m to about 6 m in EUW's Figure 3.

[3] EUW's analysis is based on an idealized model [*Thorndike*, 1992] which only includes surface energy gain and loss through radiative fluxes, so that a decrease in absorbed surface shortwave (F_{SW}) due to increased albedo (α) would be entirely compensated by a decrease in net surface longwave radiation (F_{LW}). But in CCSM3 the response to albedo increase is more complex, with comparable decreases in longwave, latent (F_{LH}), and sensible (F_{SH}) heat fluxes (Table 1).

[4] More intriguing is the role played by ice export. The export of ice from the central Arctic implies an energy gain roughly equal to the latent heat of freezing times the exported volume. For fixed ice velocity an increase in ice thickness implies a proportional increase in ice export and hence energy gain. In Table 1 the energy increase due to enhanced ice export ($-LH(\partial_t h)_D$) does almost as much (1.72 Wm^{-2}) to compensate the albedo-induced shortwave loss as the longwave, sensible, and latent heat flux changes combined. (1.83 Wm^{-2}). Ice motion is not considered in the thermodynamic analysis presented by EUW.

[5] A more important difference between Holland et al.'s experiment and EUW's theoretical treatment is the size of the shortwave flux decrease for an albedo increase of 0.08–3.46 Wm^{-2} in Table 1 versus 8 Wm^{-2} for EUW (as noted above, 0.08 is the effective increase resulting from the imposed increase of 0.13). EUW assume $F_{SW} = F_{SW\downarrow}(1 - \alpha)$ with $F_{SW\downarrow} = 100$ Wm^{-2} in the annual mean, which means an 8 Wm^{-2} loss in F_{SW} for a gain in albedo of 0.08. In the EUW analysis a 3.46 Wm^{-2} decrease in F_{SW} is equivalent to an albedo increase of 0.0346, which by their Figure 3 would yield an increase of about 1 m in thickness, twice the CCSM3 increase but much closer to CCSM3 than the change from 2 m to 6 m for $\delta\alpha = 0.08$.

[6] We find two reasons for the difference in F_{SW} change implied by an 0.08 α increase. First, the value of $F_{SW\downarrow}$ in Table 1 is 70 Wm^{-2} rather than the 100 Wm^{-2} in EUW. In EUW's calculation $F_{SW\downarrow} = 70$ Wm^{-2} implies a change of 5.6 Wm^{-2} in F_{SW} for an 0.08 increase in α. Their calculations further imply that a 5.6 Wm^{-2} F_{SW} increase (equivalent to $\delta\alpha = 0.056$) produces a thickness increase from roughly 2 to 4 m, still larger than the CCSM3 change by a factor of 4.

[7] Second, cloud cover plays an important role in the CCSM3 shortwave flux change, since the annual-mean change in F_{SW} under albedo increase is -10.4 Wm^{-2} for clear sky but only -3.46 Wm^{-2} for all sky (clear and cloudy) conditions. The smaller decrease under all sky conditions is largely explained by the 5.8 Wm^{-2} *increase* in downwelling shortwave flux. The 0.016 reduction in MJJA cloud fraction explains part of the increase ($\sim$2 Wm^{-2}), since less cloud implies more radiation reaching the surface.

[8] Multiple scattering from highly reflective clouds plays an important role in the $F_{SW\downarrow}$ increase. For a non-absorbing cloud with reflectivity r the downwelling shortwave below the cloud is given by $F_{SW\downarrow} = F_0 (1 - r)/(1 - \alpha r)$ [e.g., *Shine*, 1984], so the sensitivity to albedo change is $\partial_\alpha F_{SW\downarrow} = F_{SW\downarrow} r/(1 - r\alpha)$. For an MJJA cloud fraction of

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Table 1. Annual-Mean Energy Fluxes for an Experiment in Which Albedo Was Increased by 0.13, the Corresponding Control Run, and the Change Due to the Albedo Increase[a]

	+13%	Control	+0.13 − Ctl	r = 0.70
$F_{SW\downarrow}$	76.1	70.3	5.84	5.77[b]
$F_{SW\uparrow}$	56.2	46.8	9.30	9.26[c]
F_{SW}	20.0	23.4	−3.46	−3.49[d]
$F_{SW\downarrow}$ Clear Sky	127.4	126.6	0.83	
$F_{SW\uparrow}$ Clear Sky	88.6	77.4	11.19	
F_{SW} Clear Sky	38.9	49.2	−10.36	
F_{LW}	21.0	21.6	−0.61	
F_{SH}	1.9	2.5	−0.55	
F_{LH}	3.4	4.1	−0.67	
$-LH(\partial_t h)_D$	6.1	4.4	1.72	
$-LH(\partial_t h)_T$	−6.1	−4.4	−1.64	
MJJA Cloud	0.82	0.84	−0.016	
MJJA α_{eff}	0.72	0.64	0.08	

[a]The experiment was conducted in CCSM3 with a "slab" mixed layer ocean, a dynamic-thermodynamic sea ice model with one thickness category, and the standard atmospheric model (see *Holland et al.* [2006] for details). $(\partial_t h)_D$ and $(\partial_t h)_T$ are the thickness tendency due to dynamics and thermodynamics, respectively, the difference of which is presumably due to sampling error or incomplete adjustment to equilibrium. Statistics are averages for perennial ice gridpoints defined by a climatological September ice concentration of 0.85 or more, using the climatology from the last 10 years of a 30-year integration. Cloud fraction and albedo are reported for the MJJA months, with α_{eff} the ratio of mean downwelling to upwelling shortwave for that period. Up, down, and net shortwave fluxes in the far right column are changes calculated from the multiple scattering formula for a nonabsorbing cloud of reflectivity r = 0.70.

[b]$\delta F_{SW\downarrow} = \delta\alpha \cdot F_{SW\downarrow}\, r/(1 - r\alpha) \cdot C$, C = cloud fraction.

[c]$\delta F_{SW\uparrow} = \delta\alpha \cdot F_{SW\downarrow}\, 1/(1 - r\alpha) \cdot C + \delta\alpha\,(1 - C)\, F_{SW\downarrow}$.

[d]$\delta F_{SW} = \delta F_{SW\downarrow} - \delta F_{SW\uparrow}$.

0.82 and an initial MJJA albedo of 0.63, close approximations to the changes in up, down, and net shortwave can be made from the multiple scattering formula using $r = 0.70$. The idealized analysis used by EUW does not incorporate the mitigating effects of multiple scattering on albedo change.

[9] No doubt, albedo is tuned and such tuning compensates for a variety of model physics errors. But at least for CCSM3, minute albedo adjustments would not be sufficient to compensate for extreme thickness errors due to longwave errors induced by cloud biases. The 0.13 albedo increase in Holland et al. is at the limit of acceptable albedo adjustments for a standard CCSM version, yet the thickness change produced by it is relatively minor. The results presented here show that a number of physical mechanisms compensate for an imposed albedo change, and we suspect that the compensation for cloud-related longwave errors also comes from legitimate physical processes rather than ad hoc tuning. EUW's simple model neglects a wide range of processes important for sea ice simulation, and its use in judging climate model validity is therefore somewhat limited.

[10] Despite our disagreement with EUW's conclusions, we commend them for their goal of relating uncertainty in sea ice thickness to uncertainties in model physics.

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