Understanding Controls on Snow Albedo through Multiple Modeling Approaches

Samip Karki, Peter Larson, Jiayi Wang, and Alden Adolph
Physics Department, St. Olaf College

TRIO McNair Scholars Program ST. OLAF COLLEGE

ST. OLAF COLLEGE

Snow in the Northern Hemisphere is wet up to 30% of the season[3], but snow albedo models only represent dry snow. Our goal is to address this!

Why is snow albedo important?

- Albedo is the fraction of incoming solar radiation that is reflected.
- Snow plays an important role in controlling surface temperature and global energy budget because it covers up to 47 million square km of Earth's surface (*NSIDC* 2019) and has high albedo.
- Small changes in albedo can result in significant surface warming and snowmelt due to the positive snow albedo feedback processes.
- Many different metrics such as snow cover extent (see Figure 1), sea ice extent, and glacial recession show that snow and ice are melting.

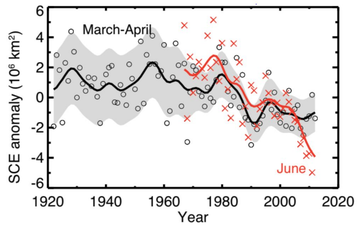


Figure 1: From *IPCC 5th Assessment Report.* Snow Cover Extent anomaly in the Northern Hemisphere showing decline in spring and summer.

What factors affect snow albedo?

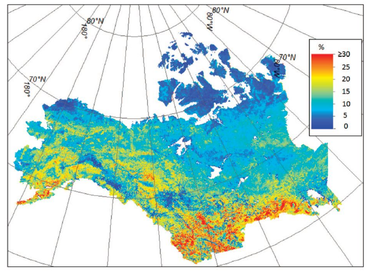


Figure 2: From *Kim et al. (2018)*. This figure is showing the percentage of time that the snow is wet within the shown region of Northern America.

- The two main intrinsic factors that have been studied which affect snow albedo are grain size and impurity content (*Tedesco et al.* 2015).
- Other factors such as packing arrangement (*He et al*. 2018), surface roughness (*Larue et al*. 2020), snow thickness, and grain shape (*Dang et al.* 2017) affect albedo.
- The presence of liquid water in snow also affects albedo, but this factor has been studied less despite frequent liquid water presence (Figure 2).

Which models are we studying?

Analytical

- One of the models we are investigating is an analytical model from *Kokhanovsky et al.* (2018).
- The goal of the model is to calculate broadband albedo (350-1500 nm) based on measurements of albedo at 3 wavelengths.
- Fundamental impact parameters of albedo:
  - density (c)
  - grain diameter (d)
  - pollution type and concentration (k_0, m)
  - property of ice (imaginary part of the index of refraction)

Ray Tracing

- The ray tracing model from *Kaempfer et al.* (2007) tracks a photon's trajectory (Figure 3) through a simulated snowpack based on fundamental snow properties and optics.
- When done on a large scale with many photons, the albedo of the snowpack is found by recording how many photons were absorbed and reflected.

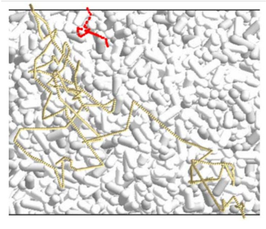


Figure 3: From *Kaempfer et al. 2007*. Red line shows trace of photon at 1000 nm and yellow line shows trace of photon at 470 nm.

How are we implementing these models?

Analytical

- We have explored the equations describing the relationships between albedo and changing snow parameters including pollution factors (m,k_0), density (c) and grain diameter (d). Figure 4 and Figure 5 show two of those relations, which match our expectations.

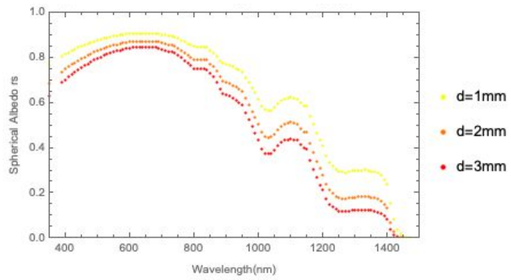


Figure 4: Analytically calculated spherical albedo (rs) vs. wavelength at different grain sizes (d=1mm, 2mm, 3mm).

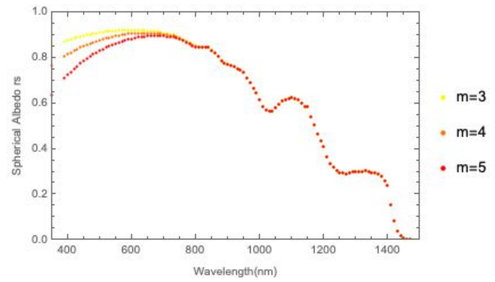


Figure 5: Analytically calculated spherical albedo (rs) vs. wavelength at different pollution conditions (m=3, m=4, m=5).

Ray Tracing

- We are recreating the ray tracing model using Matlab. So far we've worked on generating snow samples and modeling a light beam to travel through the samples.
- We simulated a snowpack by randomly generating spherical snow grains and assigning coordinates of the snowpack as air or ice (Figure 6).
- To implement ray tracing, our team is also creating a program that tracks a light beam and dictates its path using fundamental optics (Figure 7).

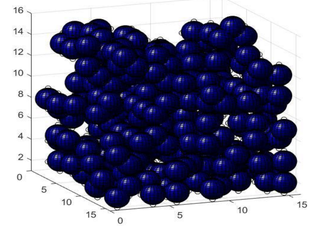


Figure 6: Randomly generated snowpack made of spherical snow grains. Iterations of the model allow for variations in grain size and prevent overlapping of snow grains (representative figure, not to scale).

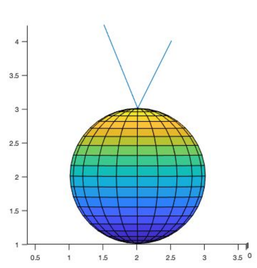


Figure 7: A simulation of a photon (represented by the blue line) reflecting from a spherical snow grain. This will eventually be applied to a simulated snowpack like the one in Figure 6. (representative figure, not to scale)

How will we improve these models?

- Both the analytical and the ray tracing models only simulate dry snow. Our goal is to improve these models by including liquid water content.
- Analytical: the total absorption (k_{tot}) in the model is due to pollution and ice, and we plan to add an absorption term due to liquid water content into k_{tot}.
- Ray tracing: to incorporate liquid water in this model, we would need to update the snowpack simulation to include a layer of liquid water around the snow grains, and change the light-tracking physics to interact appropriately with the newly added liquid water.

Acknowledgements

We would like to thank the Collaborative Undergraduate Research and Inquiry Program (CURI) and the Ronald E. McNair Post-Baccalaureate Program for making this project possible, and we look forward to continuing our research this fall and in the coming years.

Citations

1. Dang, C., Fu, Q., & Warren, S. G. (2016). Effect of snow grain shape on snow albedo. *Journal of the Atmospheric Sciences*, *73*(9), 3573-3583.
2. He, C., Y. Takano, and K.-N. Liou (2017), Close packing effects on clean and dirty snow albedo and associated climatic implications, *Geophys. Res. Lett.*, *44*, 3719–3727, doi:10.1002/2017GL072916.
3. Kim, Y., Kimball, J. S., Du, J., Schaaf, C. L., & Kirchner, P. B. (2018). Quantifying the effects of freeze-thaw transitions and snowpack melt on land surface albedo and energy exchange over Alaska and Western Canada. *Environmental Research Letters*, *13*(7), 075009.
4. Kokhanovsky, A., Lamare, M., Di Mauro, B., Picard, G., Laurent, A., Dumont, M., ... & Box, J. E. (2018). On the reflectance spectroscopy of snow. *The Cryosphere*, *12*(7), 2371.
5. Kokhanovsky, A. A., & Zege, E. P. (2004). Scattering optics of snow. *Applied Optics*, *43*(7), 1589-1602.
6. Larue, F., Picard, G., Arnaud, L., Ollivier, I., Delcourt, C., Lamare, M., . . . Dumont, M. (2020). Snow albedo sensitivity to macroscopic surface roughness using a new ray-tracing model. *The Cryosphere, 14*(5), 1651-1672. doi:10.5194/tc-14-1651-2020
7. NSIDC, State of the Cryosphere: Northern Hemisphere Snow. Last Update: November 1, 2019. Accessed: July 2020.
8. Stocker, T. F., Qin, D., Plattner, G., Tignor, M., Allen, S., Boschung, J., ... & Midgley, P. M. (2013). Climate change 2013: The physical science basis, working group 1 (wg1) contribution to the intergovernmental panel on climate change (ipcc) 5th assessment report (ar5). *Cambridge, UK and New York, New York, USA*.
9. Tedesco, M., S. Doherty, W. Warren, M. Tranter, J. Stroeve, X. Fettweis, and P. Alexander (2015), What darkens the Greenland ice sheet?, *Eos, 96*, doi:10.1029/2015EO035773. Published on 17 September 2015.

TRIO
McNair Scholars Program
ST. OLAF COLLEGE

Understanding Controls on Snow Albedo through Multiple Modeling Approaches

Samip Karki, Peter Larson, Jiayi Wang, and Alden Adolph
Physics Department, St. Olaf College

ST. OLAF COLLEGE

Snow in the Northern Hemisphere is wet up to 30% of the season[3], but snow albedo models only represent dry snow. Our goal is to address this!

Why is snow albedo important?

- Albedo is the fraction of incoming solar radiation that is reflected.
- Snow plays an important role in controlling surface temperature and global energy budget because it covers up to 47 million square km of Earth's surface (*NSIDC* 2019) and has high albedo.
- Small changes in albedo can result in significant surface warming and snowmelt due to the positive snow albedo feedback processes.
- Many different metrics such as snow cover extent (see Figure 1), sea ice extent, and glacial recession show that snow and ice are melting.

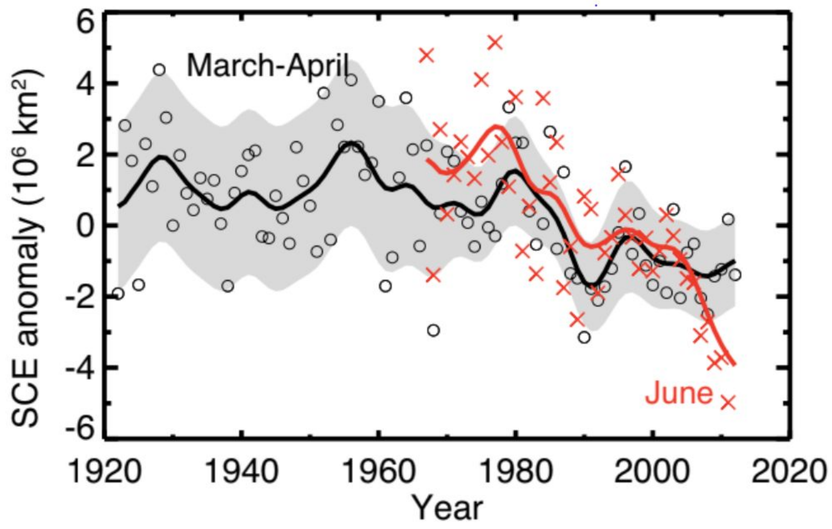


Figure 1: From *IPCC 5th Assessment Report.* Snow Cover Extent anomaly in the Northern Hemisphere showing decline in spring and summer.

TRIO
McNair Scholars Program
ST. OLAF COLLEGE

Understanding Controls on Snow Albedo through Multiple Modeling Approaches

Samip Karki, Peter Larson, Jiayi Wang, and Alden Adolph
Physics Department, St. Olaf College

ST. OLAF COLLEGE

What factors affect snow albedo?

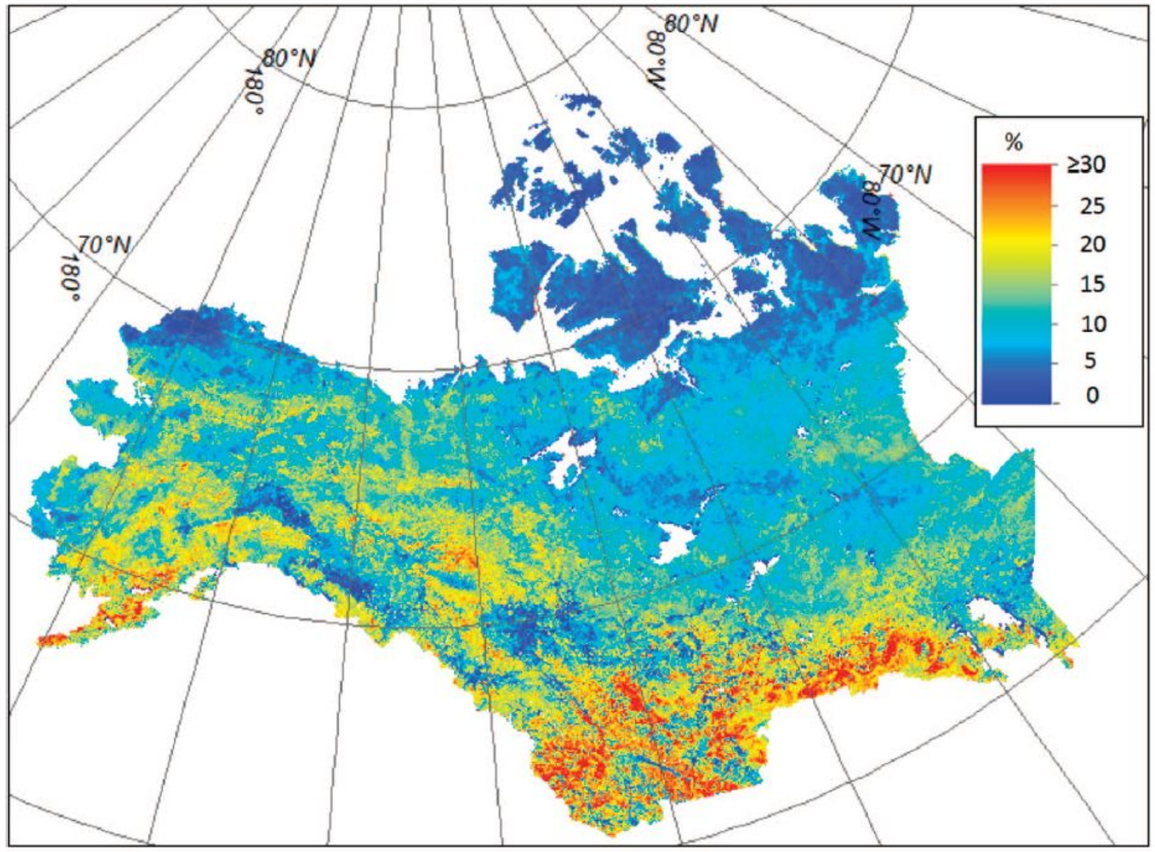


Figure 2: From Kim et al. (2018). This figure is showing the percentage of time that the snow is wet within the shown region of Northern America.

- The two main intrinsic factors that have been studied which affect snow albedo are grain size and impurity content (Tedesco et al. 2015).
- Other factors such as packing arrangement (He et al. 2018), surface roughness (Larue et al. 2020), snow thickness, and grain shape (Dang et al. 2017) affect albedo.
- The presence of liquid water in snow also affects albedo, but this factor has been studied less despite frequent liquid water presence (Figure 2).

Understanding Controls on Snow Albedo through Multiple Modeling Approaches

Samip Karki, Peter Larson, Jiayi Wang, and Alden Adolph
Physics Department, St. Olaf College

Which models are we studying?

Analytical

- One of the models we are investigating is an analytical model from *Kokhanovsky et al.* (2018).
- The goal of the model is to calculate broadband albedo (350-1500 nm) based on measurements of albedo at 3 wavelengths.
- Fundamental impact parameters of albedo:
  - density (c)
  - grain diameter (d)
  - pollution type and concentration (k_0, m)
  - property of ice (imaginary part of the index of refraction)

TRIO
McNair Scholars Program
ST. OLAF COLLEGE

Understanding Controls on Snow Albedo through Multiple Modeling Approaches

Samip Karki, Peter Larson, Jiayi Wang, and Alden Adolph
Physics Department, St. Olaf College

ST. OLAF COLLEGE

How are we implementing these models?

Analytical

- We have explored the equations describing the relationships between albedo and changing snow parameters including pollution factors (m,k_0), density (c) and grain diameter (d). Figure 4 and Figure 5 show two of those relations, which match our expectations.

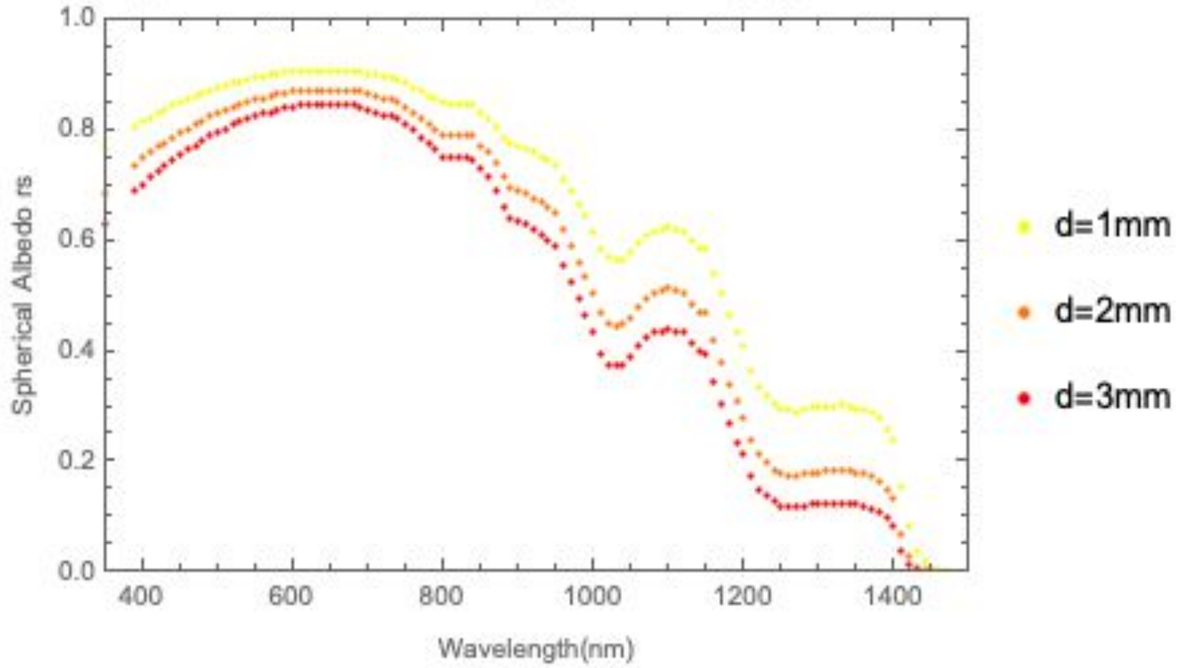


Figure 4: Analytically calculated spherical albedo (rs) vs. wavelength at different grain sizes (d=1mm, 2mm, 3mm).

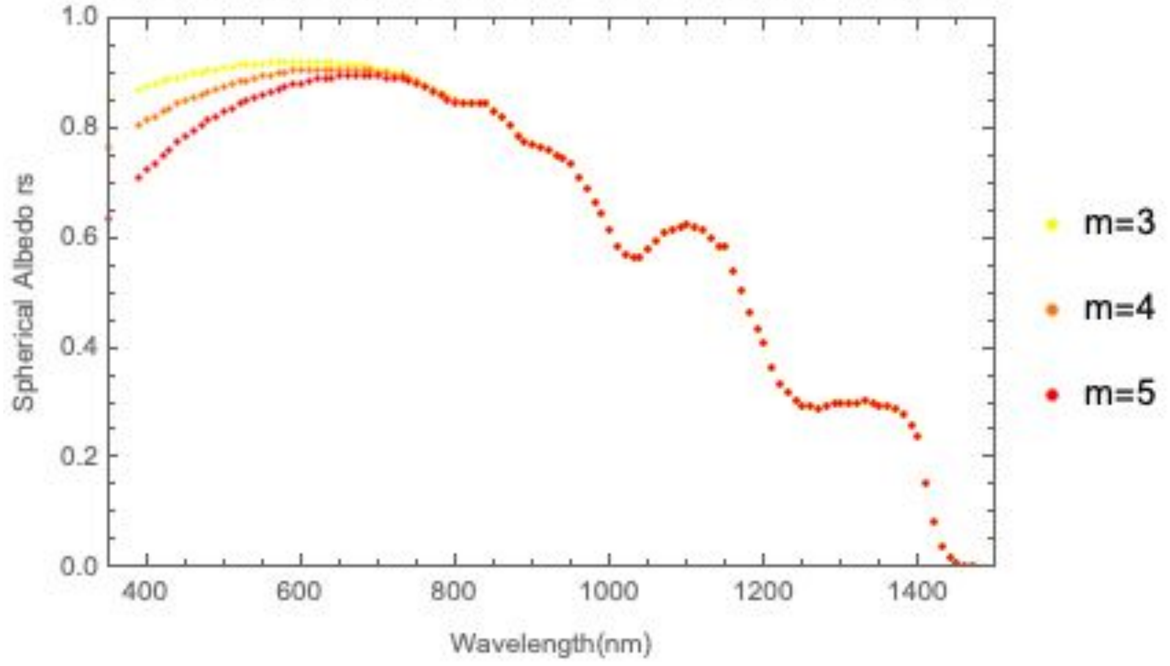


Figure 5: Analytically calculated spherical albedo (rs) vs. wavelength at different pollution conditions (m=3, m=4, m=5).

TRIO
McNair Scholars Program
ST. OLAF COLLEGE

Understanding Controls on Snow Albedo through Multiple Modeling Approaches

Samip Karki, Peter Larson, Jiayi Wang, and Alden Adolph
Physics Department, St. Olaf College

ST. OLAF COLLEGE

Which models are we studying?

Ray Tracing

- The ray tracing model from *Kaempfer et al.* (2007) tracks a photon's trajectory (Figure 3) through a simulated snowpack based on fundamental snow properties and optics.
- When done on a large scale with many photons, the albedo of the snowpack is found by recording how many photons were absorbed and reflected.

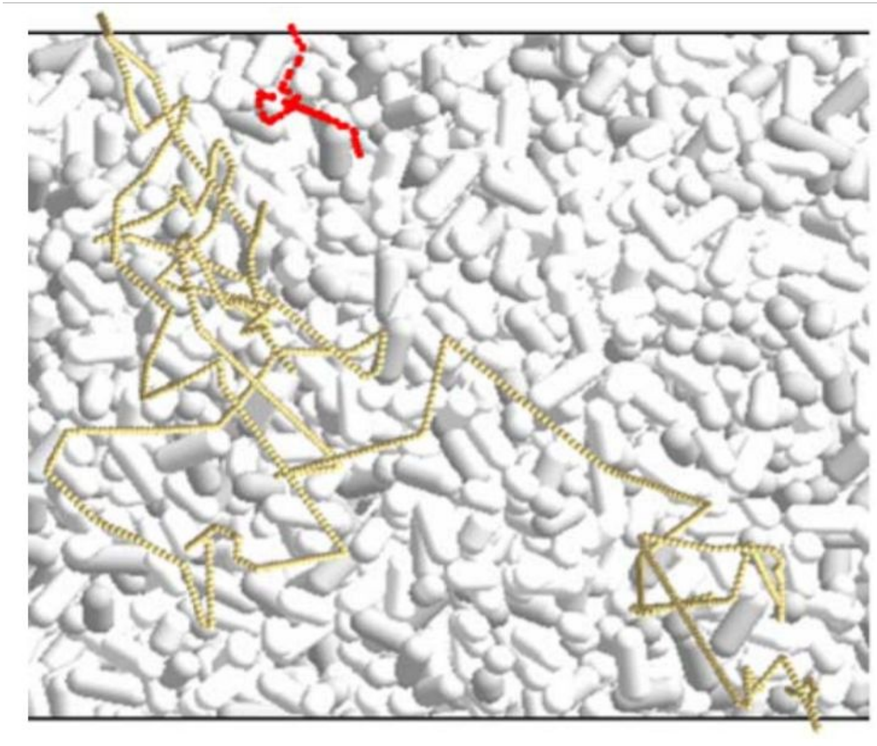


Figure 3: From *Kaempfer et al. 2007*. Red line shows trace of photon at 1000 nm and yellow line shows trace of photon at 470 nm.

TRIO
McNair Scholars Program
ST. OLAF COLLEGE

Understanding Controls on Snow Albedo through Multiple Modeling Approaches

Samip Karki, Peter Larson, Jiayi Wang, and Alden Adolph
Physics Department, St. Olaf College

ST. OLAF COLLEGE

How are we implementing these models?

Ray Tracing

- We are recreating the ray tracing model using Matlab. So far we've worked on generating snow samples and modeling a light beam to travel through the samples.
- We simulated a snowpack by randomly generating spherical snow grains and assigning coordinates of the snowpack as air or ice (Figure 6).
- To implement ray tracing, our team is also creating a program that tracks a light beam and dictates its path using fundamental optics (Figure 7).

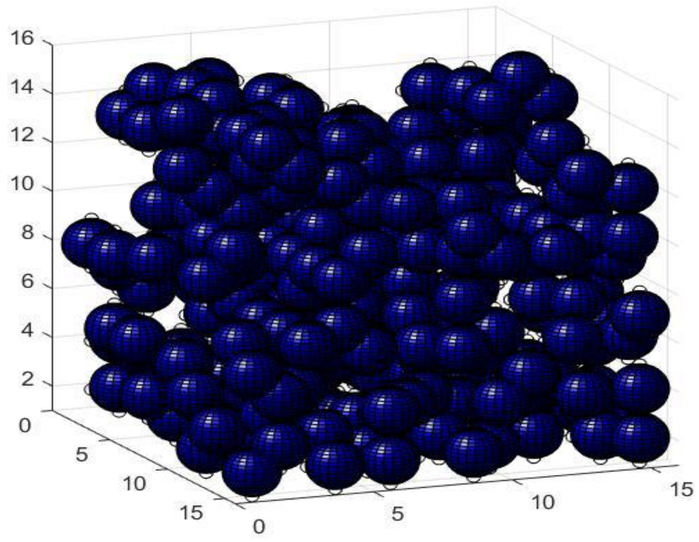


Figure 6: Randomly generated snowpack made of spherical snow grains. Iterations of the model allow for variations in grain size and prevent overlapping of snow grains (representative figure, not to scale).

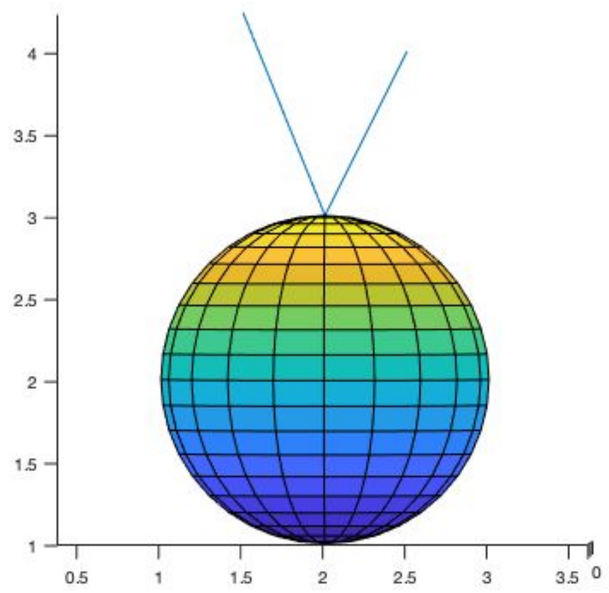


Figure 7: A simulation of a photon (represented by the blue line) reflecting from a spherical snow grain. This will eventually be applied to a simulated snowpack like the one in Figure 6. (representative figure, not to scale)

TRIO
McNair Scholars Program
ST. OLAF COLLEGE

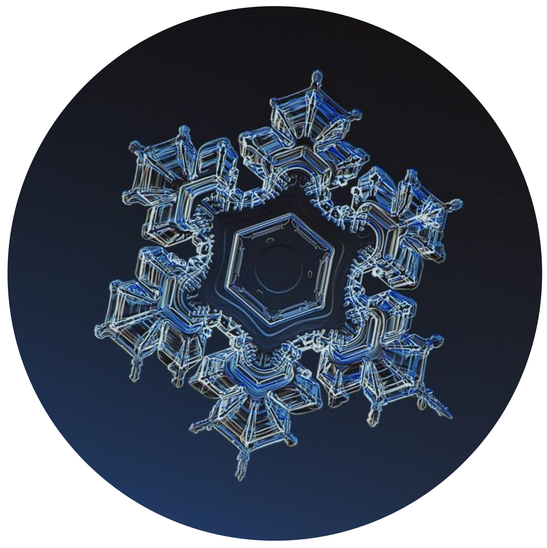
Understanding Controls on Snow Albedo through Multiple Modeling Approaches

Samip Karki, Peter Larson, Jiayi Wang, and Alden Adolph
Physics Department, St. Olaf College

ST. OLAF COLLEGE

How will we improve these models?

- Both the analytical and the ray tracing models only simulate dry snow. Our goal is to improve these models by including liquid water content.
- Analytical: the total absorption (k_{tot}) in the model is due to pollution and ice, and we plan to add an absorption term due to liquid water content into k_{tot}.
- Ray tracing: to incorporate liquid water in this model, we would need to update the snowpack simulation to include a layer of liquid water around the snow grains, and change the light-tracking physics to interact appropriately with the newly added liquid water.



TRIO
McNair Scholars Program
ST. OLAF COLLEGE

Understanding Controls on Snow Albedo through Multiple Modeling Approaches

Samip Karki, Peter Larson, Jiayi Wang, and Alden Adolph
Physics Department, St. Olaf College

ST. OLAF COLLEGE

Acknowledgements and Citations

We would like to thank the Collaborative Undergraduate Research and Inquiry Program (CURI) and the Ronald E. McNair Post-Baccalaureate Program for making this project possible, and we look forward to continuing our research this fall and in the coming years.

1. Dang, C., Fu, Q., & Warren, S. G. (2016). Effect of snow grain shape on snow albedo. *Journal of the Atmospheric Sciences*, *73*(9), 3573-3583.
2. He, C., Y. Takano, and K.-N. Liou (2017), Close packing effects on clean and dirty snow albedo and associated climatic implications, *Geophys. Res. Lett., 44*, 3719–3727, doi:10.1002/2017GL072916.
3. Kim, Y., Kimball, J. S., Du, J., Schaaf, C. L., & Kirchner, P. B. (2018). Quantifying the effects of freeze-thaw transitions and snowpack melt on land surface albedo and energy exchange over Alaska and Western Canada. *Environmental Research Letters*, *13*(7), 075009.
4. Kokhanovsky, A., Lamare, M., Di Mauro, B., Picard, G., Laurent, A., Dumont, M., ... & Box, J. E. (2018). On the reflectance spectroscopy of snow. *The Cryosphere*, *12*(7), 2371.
5. Kokhanovsky, A. A., & Zege, E. P. (2004). Scattering optics of snow. *Applied Optics*, *43*(7), 1589-1602.
6. Larue, F., Picard, G., Arnaud, L., Ollivier, I., Delcourt, C., Lamare, M., . . . Dumont, M. (2020). Snow albedo sensitivity to macroscopic surface roughness using a new ray-tracing model. *The Cryosphere, 14*(5), 1651-1672. doi:10.5194/tc-14-1651-2020
7. NSIDC, State of the Cryosphere: Northern Hemisphere Snow. Last Update: November 1, 2019. Accessed: July 2020.
8. Stocker, T. F., Qin, D., Plattner, G., Tignor, M., Allen, S., Boschung, J., ... & Midgley, P. M. (2013). Climate change 2013: The physical science basis, working group 1 (wg1) contribution to the intergovernmental panel on climate change (ipcc) 5th assessment report (ar5). *Cambridge, UK and New York, New York, USA*.
9. Tedesco, M., S. Doherty, W. Warren, M. Tranter, J. Stroeve, X. Fettweis, and P. Alexander (2015), What darkens the Greenland ice sheet?, *Eos, 96*, doi:10.1029/2015EO035773. Published on 17 September 2015.

Understanding Controls on Snow Albedo through Multiple Modeling Approaches

Samip Karki, Peter Larson, Jiayi Wang, and Alden Adolph
Physics Department, St. Olaf College

TRIO McNair Scholars Program ST. OLAF COLLEGE

ST. OLAF COLLEGE

Snow in the Northern Hemisphere is wet up to 30% of the season[3], but snow albedo models only represent dry snow. Our goal is to address this!

Why is snow albedo important?

- Albedo is the fraction of incoming solar radiation that is reflected.
- Snow plays an important role in controlling surface temperature and global energy budget because it covers up to 47 million square km of Earth's surface (*NSIDC* 2019) and has high albedo.
- Small changes in albedo can result in significant surface warming and snowmelt due to the positive snow albedo feedback processes.
- Many different metrics such as snow cover extent (see Figure 1), sea ice extent, and glacial recession show that snow and ice are melting.

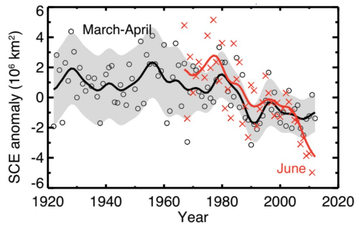


Figure 1: From *IPCC 5th Assessment Report.* Snow Cover Extent anomaly in the Northern Hemisphere showing decline in spring and summer.

What factors affect snow albedo?

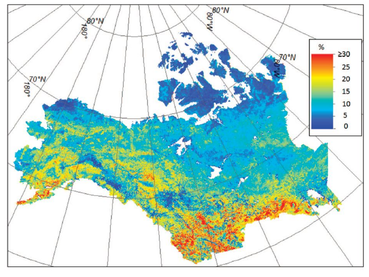


Figure 2: From *Kim et al. (2018)*. This figure is showing the percentage of time that the snow is wet within the shown region of Northern America.

- The two main intrinsic factors that have been studied which affect snow albedo are grain size and impurity content (*Tedesco et al.* 2015).
- Other factors such as packing arrangement (*He et al*. 2018), surface roughness (*Larue et al*. 2020), snow thickness, and grain shape (*Dang et al.* 2017) affect albedo.
- The presence of liquid water in snow also affects albedo, but this factor has been studied less despite frequent liquid water presence (Figure 2).

Which models are we studying?

Analytical

- One of the models we are investigating is an analytical model from *Kokhanovsky et al.* (2018).
- The goal of the model is to calculate broadband albedo (350-1500 nm) based on measurements of albedo at 3 wavelengths.
- Fundamental impact parameters of albedo:
  - density (c)
  - grain diameter (d)
  - pollution type and concentration (k_0, m)
  - property of ice (imaginary part of the index of refraction)

Ray Tracing

- The ray tracing model from *Kaempfer et al.* (2007) tracks a photon's trajectory (Figure 3) through a simulated snowpack based on fundamental snow properties and optics.
- When done on a large scale with many photons, the albedo of the snowpack is found by recording how many photons were absorbed and reflected.

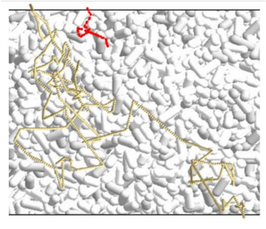


Figure 3: From *Kaempfer et al. 2007*. Red line shows trace of photon at 1000 nm and yellow line shows trace of photon at 470 nm.

How are we implementing these models?

Analytical

- We have explored the equations describing the relationships between albedo and changing snow parameters including pollution factors (m,k_0), density (c) and grain diameter (d). Figure 4 and Figure 5 show two of those relations, which match our expectations.

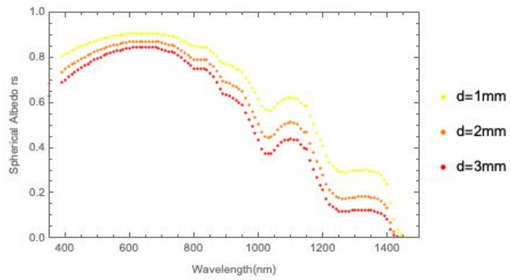


Figure 4: Analytically calculated spherical albedo (rs) vs. wavelength at different grain sizes (d=1mm, 2mm, 3mm).

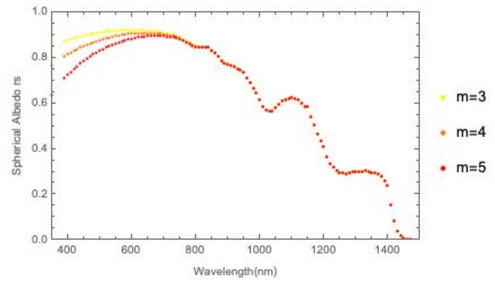


Figure 5: Analytically calculated spherical albedo (rs) vs. wavelength at different pollution conditions (m=3, m=4, m=5).

Ray Tracing

- We are recreating the ray tracing model using Matlab. So far we've worked on generating snow samples and modeling a light beam to travel through the samples.
- We simulated a snowpack by randomly generating spherical snow grains and assigning coordinates of the snowpack as air or ice (Figure 6).
- To implement ray tracing, our team is also creating a program that tracks a light beam and dictates its path using fundamental optics (Figure 7).

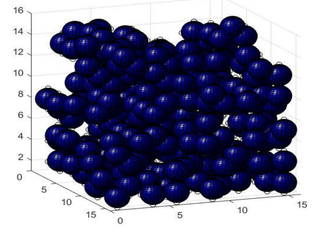


Figure 6: Randomly generated snowpack made of spherical snow grains. Iterations of the model allow for variations in grain size and prevent overlapping of snow grains (representative figure, not to scale).

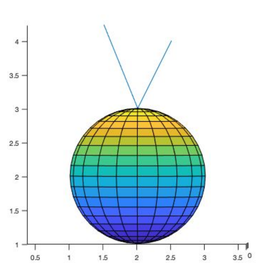


Figure 7: A simulation of a photon (represented by the blue line) reflecting from a spherical snow grain. This will eventually be applied to a simulated snowpack like the one in Figure 6. (representative figure, not to scale)

How will we improve these models?

- Both the analytical and the ray tracing models only simulate dry snow. Our goal is to improve these models by including liquid water content.
- Analytical: the total absorption (k_{tot}) in the model is due to pollution and ice, and we plan to add an absorption term due to liquid water content into k_{tot}.
- Ray tracing: to incorporate liquid water in this model, we would need to update the snowpack simulation to include a layer of liquid water around the snow grains, and change the light-tracking physics to interact appropriately with the newly added liquid water.

Acknowledgements

We would like to thank the Collaborative Undergraduate Research and Inquiry Program (CURI) and the Ronald E. McNair Post-Baccalaureate Program for making this project possible, and we look forward to continuing our research this fall and in the coming years.

Citations

1. Dang, C., Fu, Q., & Warren, S. G. (2016). Effect of snow grain shape on snow albedo. *Journal of the Atmospheric Sciences*, *73*(9), 3573-3583.
2. He, C., Y. Takano, and K.-N. Liou (2017), Close packing effects on clean and dirty snow albedo and associated climatic implications, *Geophys. Res. Lett.*, *44*, 3719–3727, doi:10.1002/2017GL072916.
3. Kim, Y., Kimball, J. S., Du, J., Schaaf, C. L., & Kirchner, P. B. (2018). Quantifying the effects of freeze-thaw transitions and snowpack melt on land surface albedo and energy exchange over Alaska and Western Canada. *Environmental Research Letters*, *13*(7), 075009.
4. Kokhanovsky, A., Lamare, M., Di Mauro, B., Picard, G., Laurent, A., Dumont, M., ... & Box, J. E. (2018). On the reflectance spectroscopy of snow. *The Cryosphere*, *12*(7), 2371.
5. Kokhanovsky, A. A., & Zege, E. P. (2004). Scattering optics of snow. *Applied Optics*, *43*(7), 1589-1602.
6. Larue, F., Picard, G., Arnaud, L., Ollivier, I., Delcourt, C., Lamare, M., . . . Dumont, M. (2020). Snow albedo sensitivity to macroscopic surface roughness using a new ray-tracing model. *The Cryosphere, 14*(5), 1651-1672. doi:10.5194/tc-14-1651-2020
7. NSIDC, State of the Cryosphere: Northern Hemisphere Snow. Last Update: November 1, 2019. Accessed: July 2020.
8. Stocker, T. F., Qin, D., Plattner, G., Tignor, M., Allen, S., Boschung, J., ... & Midgley, P. M. (2013). Climate change 2013: The physical science basis, working group 1 (wg1) contribution to the intergovernmental panel on climate change (ipcc) 5th assessment report (ar5). *Cambridge, UK and New York, New York, USA*.
9. Tedesco, M., S. Doherty, W. Warren, M. Tranter, J. Stroeve, X. Fettweis, and P. Alexander (2015), What darkens the Greenland ice sheet?, *Eos, 96*, doi:10.1029/2015EO035773. Published on 17 September 2015.