Proof of Concept: Modeling hail trajectories and the water isotopic composition of the hail to better understand hail formation and hailstorms

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Overview

Hail is the most consistently damaging impact of severe thunderstorms producing losses in the United States in excess of $10 billion each year over the past decade. Urban areas are particularly vulnerable. For example, on May 8th 2017, a severe thunderstorm formed over the western suburbs of Denver producing hailstones up to 2.75″ in diameter, pummeling cars and structures causing a total of $1.4 billion in damage. With an awareness of the damage that hailstorms produce and the advances in recent modeling and observational capabilities, we have developed this proposal, discussed below.

Hailstorms in North America

The effects of hailstorms extend beyond the losses of individual homeowners, as commercial interests, renewable energy producers, both civilian and military aviation, and agriculture experience significant impacts during hailstorms. Yet, with improved detection and prediction of severe hail and understanding of hail characteristics and impacts at the surface, a good portion of this monetary loss could be avoided: for example, aircraft could be moved or rerouted with better forecasts, or closer to home people could move their automobiles under protective covering (garages, etc.). Uncertainties associated with the prediction of hail falling to the ground- the time and location, nowcasting of hail, etc., motivate the need for improved modeling of hail. Furthermore, improved modeling of hail could facilitate better prediction of hail in a changing climate (Prein and Heymsfield, 2020).

Modeling the Growth of Hail

The growth of hail is a process whereby ice particles collect droplets (become rimed) and then with sufficient liquid water and time in the updrafts, graupel and then hail will result. The modeling of hail requires knowledge of the steps leading from ice particles to hail, the physical properties of the particles and the number of and size of the particles per unit volume of air (size distributions). The most recent WRF-ARW version (Skamarock et al., 2019), including the Thompson and Morrison microphysics parameterizations, considers the development of hail: rimed particles, including rimed ice snow crystals, that develop into graupel, which then grows into hail. In these parameterizations, many simplifying assumptions of the growth of hail are made. Using new observations, these assumptions could be updated and thereby significantly improved.

One goal of this proposal is to improve upon the parameterizations used to represent the microphysics of the growth of hail. Specifically, these are the masses, terminal velocities, and concentrations of particles as they rime and grow to hail. Many of the parameterizations date back to the 1970's and 1980's, yet more recent work improves upon them. For example, Heymsfield et al. (2018) uses recent measurements and theoretical considerations to improve the representations of the physical properties of hail, including size-dependent relationships for hailstone mass, terminal velocity, and kinetic energy. A recent study by Field et al. (2019) reports on a comprehensive set of microphysical data from the hail penetrating T28 aircraft yielding much improved information on the properties of hail within hailstorms.

Explanation of the scientific merit of the proposal

There remain several basic questions about how hail develops. These include:

1. What type of particles do hailstone embryos consist of? How do these properties change with respect to temperature? Storm type?
2. Where are the embryo source regions typically positioned with respect to the updraft?
3. How do changes in the embryo characteristics, and source region location, impact hailstone trajectories and final hail size?

How can we assess whether WRF, without and with the improvements we make, help us to address these questions? One of the more powerful natural tracers of hailstone growth is the isotopic composition of the water that freezes (rimes) onto the embryonic ice crystal. Since the 1960s, investigators have used differences in the isotopic composition of the “onion-like” or “tree-ring like” layers that form the hailstone to determine where, within the storm cloud, moisture rimed onto the stone. The early pioneering studies were, however, limited by a lack of isotopic information about both the storm moisture source (the inflowing water vapor) and the cloud-free environment and by their reliance on overly simple one-dimensional cloud models. Together, these factors resulted in significant uncertainties in their estimates of hailstone growth.

Here, we propose to put water isotope tracers in WRF, to use high-frequency, real-time measurements of water vapor isotope ratios near hail-producing storms, and to collect and measure the isotopic composition of hailstones to test our understanding of hailstone growth and evaluate WRF’s representation of this process. To estimate the isotopic composition of the storm moisture source (inflow) and the cloud-free environment, we will take advantage of measurements of water vapor’s isotopic composition from several existing National Ecological Observatory Network (NEON) stations, positioned at Niwot Ridge and in North Sterling, Colorado. We also hope to deploy a third isotopic analyzer at a location in between (either at UCAR’s Foothills campus or at the University of Northern Colorado in Greeley). We will collect hailstones at the ground, section them, and get an approximate estimate of their growth trajectories for comparison with modeled growth trajectories. The sizes and kinetic energy (damage potential) of the falling hail will also be measured from a newly developed instrument. The locations of the chaff, and those of the hail at the ground, will be compared to radar data from the NOAA radars at Denver, Cheyenne WY, and Goodland, KS. Also, the modeled locations of the hail at the ground will be compared with the CocoRaHS hailpad network data. This study will be done for cases of opportunity in NE Colorado during the early to mid-summer of 2021. This effort will be a proof of concept for a proposal which a large group of university, private sector, and NCAR investigators plan to submit to the National Science Foundation.

Approach

There are 5 tasks that we propose to complete:

1) Apply the latest version of WRF-ARW to model selected hailstorm cases over eastern Colorado from the summer of 2021. WRF will be run at convective-permitting resolutions using a 3-km domain containing a 1-km nest over the Colorado region and initialized with the operational High Resolution Rapid Refresh (HRRR) model. The runs will contain three sets of tracers: i) an isotopic composition tracer, ii) a”chaff” tracer, (mimicking a highly reflective material that radar can detect), for the purpose of identifying hail formation and growth regions, and iii) a tracer with a fixed sedimentation velocity, to mimic a GPS device that we hope to use for future hail studies.

Some of the specifics are as follows: we will (1) add tracers of hail and/or chaff to WRF, 2) add WRF isotopic tracers, and 3) compare and verify model forecasts for multiple cases.

2) We will add improvements to two hail microphysics parameterizations, using recent studies that have improved the estimate of hail properties such as mass, terminal velocities (Heymsfield et al. 2018) and in-situ observations of hail size distributions (Field et al. 2018). For example, Rebecca Adams-Selin has already incorporated the newly recommended graupel and hail relationships in Field et al. (2018) into the Morrison microphysics scheme, and she will provide that code to Jim Bresch. We will then run the model without and with the microphysics modifications for the selected hailstorms. (Also, see 4).

3) Compare the results to two different versions of the CAM-HAILCAST hail trajectory model (Adams-Selin and Ziegler 2016; Adams-Selin et al. 2019). CAM-HAILCAST is already embedded within WRFV4.2 and uses updraft and microphysical profiles from within WRF columns to drive a one-dimensional pseudo-Lagrangian hail trajectory model. In addition, a custom three-dimensional version of the CAM-HAILCAST hail trajectory model has been developed that uses WRF data as input. The one-dimensional pseudo-Lagrangian option, operationally deployed in the High Resolution Rapid Refresh (HRRR) model, uses a time-dependent updraft multiplier in an attempt to parameterize hailstone motion through a one-dimensional updraft. The three-dimensional version, conversely, is able to take advantage of the full three-dimensional CAM simulated updraft and microphysical information. By comparing the resulting hail sizes, as well as hail density and terminal velocity, from both trajectory model versions, the importance of three-dimensional updraft structure in hail prediction can be evaluated. Further comparison of the CAM-HAILCAST hail trajectory models directly to the microphysical parameterization output from (1) and (2) can reveal the sensitivity of hail growth to differing representation of physical processes, including riming, water retention, and updated terminal velocity relationships (e.g., Heymsfield et al. 2018). Dr. Rebecca Adams-Selin (Atmospheric and Environmental Research), developer of the CAM-HAILCAST code in conjunction with the National Severe Storm Laboratory (NSSL), will provide the three-dimensional version of CAM-HAILCAST to Dr. Bresch and aid in its deployment and simulations.

4) Measure the water vapor isotopic composition at select sites in NE Colorado. Instruments that measure water vapor's isotope ratios are currently run by the National Ecological Observatory, and all data are freely available for public use. A third instrument will be provided and deployed by EOL's Adriana Bailey and Prof. Darin Toohey, University of Colorado. We will also collect hailstones from the selected storms and measure their water isotopic composition. Charlie Knight (MMM) will section the hailstones such that the isotopic composition of the layers can be analyzed. This information will provide an estimate of the temperature where the riming (condensate) was added to the hailstones during their growth so that we can infer the hail trajectories during their growth. This information can additionally be used to directly validate the HAILCAST hail trajectory model.

5) Convene an NCAR workshop to compare WRF and HAILCAST to other models. The substance of this workshop can build upon the North American Hail Workshop held at NCAR in 2018 (Heymsfield and Giammanco, 2020). Use the measurements from 5) to evaluate the results of the model calculations for selected hailstorms in NE Colorado. Discuss possible improvements (as deemed desirable) to WRF.

Specifically, objectives 1-2 and 4 above are consistent with NCAR Strategic Plan section 3.3c: *Conducting field programs and analysis targeted at understanding the processes with the largest uncertainties by deploying innovative observations and data assimilation techniques to quantify model error and improve physical parameterizations.* Objective 4 addresses the stated NCAR goal of:*Deploying novel observations and advancing models and data assimilation techniques focused on the urban boundary layer and surrounding environment. (Section 3.3.b) and Developing new observation capabilities to complement process and modeling studies (Section 4.b).*

Anticipated Outcome and Metrics

This project has implications beyond the specific tasks and goals of the project. These include the following,

1. A plan is underway to submit a proposal to the National Science Foundation for a project called *In-Situ Collaborative Experiment for Collection of Hail In the Plains* (ICECHIP). ICECHIP proposes a comprehensive, geographically targeted field campaign to study hail during 3 weeks in each of June 2023 and 2024. The primary scientific goals of the project include: characterizing the trajectory and fall characteristics of hailstones within hail producing thunderstorms, understanding the contributions of near and sub-cloud air masses to the development, growth, and melting of hail, classifying surface properties of hailstones and identifying surface impacts and hailstone growth regimes, capturing the evolution of the convective updraft in relation to hail trajectories, and improved characterization of radar relationships including hail scattering and melt.. Several university and private sector students and scientists are involved in this project. Our project will provide a proof of concept for a number of goals of ICECHIP, including testing new instruments and analysis techniques, improvements to WRF, testing of isotopic and chaff tracers both in WRF, releasing chaff in the updrafts, and identifying it from radar signatures, thereby facilitating the planning of ICECHIP and the likelihood of a successful proposal to NSF.
2. Our project is cross-lab, involving scientists in both MMM and EOL.
3. University of Colorado faculty, staff, and possibly students will be involved in our project.
4. A workshop will be held to assess the performance of WRF without and with improvements, to evaluate the performance of WRF as a tool for forecasting hail, and for comparison with microphysical schemes (Thompson, Morrison), other models (HAILCAST), and to identify a path forward for hail forecast models.

Why Is This Proposal Transformational?

1. Use of water isotopes, both in the model and from observations at the ground, will lead to better knowledge of how and where hail develops.
2. The use of chaff, both in the model and using radar, will provide new knowledge of how hail develops, hail trajectories, air vertical motions in hailstorms, and entrainment.
3. Both NCAR MMM and EOL will collaborate on a project that is of interest to both labs. We will be working with university and private sector partners the University of Colorado and Atmospheric and Environmental Research.

Metrics

Our group will be doing the WRF modeling (with some updated microphysics), together with collecting hailstones and measuring their isotopic composition. In the model, we will put in the water isotopic composition and chaff tracers. The chaff tracer will be to simulate the movement of radar-detectable chaff. Our “proof of concept” will be to evaluate how well the model is reproducing hail trajectories and the water isotopic composition of the hail. With the model, we can evaluate where the best location relative to the updrafts would be to release chaff.

Specific metrics include:

1. How well hail size and mass and the hail embryo type is predicted at the ground relative to the observations. Quantified skill for hail characteristic forecasts from both WRF microphysical parameterizations and the CAM-HAILCAST hail trajectory models. Evaluation of skill here will go beyond simple forecasts of hail size to include trajectory evaluation via released tracers and isotopic analysis of collected hailstones, simulated model updraft strength and structure via chaff tracking.
2. Comparison of predicted versus observed hail water isotopic composition.

Timeline

Our intention is to begin the WRF model improvements as soon as funds from this proposal are available. In addition to Jim Bresch’s expertise, this will involve discussions with Rebecca Adams-Selin. We hope to conduct the field program in June and July, 2021-identifying suitable hailstorms for collecting hail, using the University of Colorado unmanned aircraft for releasing chaff (see Appendix for details), and for running the model experiments. Our focus will be on about three or four hailstorms during the period. If for safety reasons-health concerns due to the Coronavirus, we will delay our field phase by one year. We propose to conduct the workshop in early 2022, even if the field program is delayed a year, as we will be well along the way of making the model improvements and with comparisons with other models.

Budget

The PSIF burdened cost for this effort is $123,045 as detailed in the spreadsheet, and the NCAR cosponsorship of Andy Heymsfield and Adriana Bailey as PI’s is $71,811.

References

Adams-Selin, R. D., A. J. Clark, C. J. Melick, S. R. Dembek, I. L. Jirak and C. L. Ziegler, 2019: Evolution of WRF-HAILCAST during the 2014–16 NOAA/Hazardous Weather Testbed Spring Forecasting Experiments. *Wea. Forecasting*, **34**, 61-79, https://doi.org/10.1175/WAF-D-18-0024.1

Adams-Selin, R. D., and C. L. Ziegler, 2016: Forecasting hail using a one-dimensional hail growth model within WRF. *Mon. Wea. Rev.*, **144**, 4919–4939, https://doi.org/10.1175/MWR-D-16-0027.1.

Bailey, I. H., J. R. Hulston, W. C. Macklin, W. C. and J. R. Stewart, 1969: On the isotopic composition of hailstones. *J. Atm. Sci.*, **26**, 689–694.

Adams-Selin, R. D., A. J. Clark, C. J. Melick, S. R. Dembek, I. L. Jirak and C. L. Ziegler, 2019: Evolution of WRF-HAILCAST during the 2014–16 NOAA/Hazardous Weather Testbed Spring Forecasting Experiments. *Wea. Forecasting*, **34**, 61-79, https://doi.org/10.1175/WAF-D-18-0024.1

Adams-Selin, R. D., and C. L. Ziegler, 2016: Forecasting hail using a one-dimensional hail growth model within WRF. *Mon. Wea. Rev.*, **144**, 4919–4939, https://doi.org/10.1175/MWR-D-16-0027.1.

Bailey, I. H., J. R. Hulston, W. C. Macklin, W. C. and J. R. Stewart, 1969: On the isotopic composition of hailstones. *J. Atm. Sci.*, **26**, 689–694.

Federer, B., J. Jouzel, and A. Waldvogel, 1978: Hailstone trajectories determined from crystallography, deuterium content and radar backscattering. *Pageoph*, **116**, 112–129.

Field, P. R., A. J. Heymsfield, A. G. Detwiler, and J. M. Wilkinson, 2019: Normalized hail particle size distributions from the T-28 storm-penetrating aircraft. *J. Atmos. Meteor. Climatol.*, **58**, 231–245.

Heymsfield, A., Szakáll, M., Jost, A., Giammanco, I., & Wright, R. (2018). A Comprehensive Observational Study of Graupel and Hail Terminal Velocity, Mass Flux, and Kinetic Energy, *J. Atmos. Sci.*, ***75*****(11)**, 3861-3885.

Heymsfield, A. J., and I. M. Giammanco, 2020: A Workshop on North American Hail and Hailstorms: What Next?, *Bulletin of the American Meteorological Society*, **101(9)**, E1576-E1583

Jouzel, J., L. Merlivat, and E. Roth, 1975: Isotopic study of hail. *J. Geoph. Res.* **80**, 5015–5030.

Prein, A. F. and A. J. Heymsfield, 2020: Increased melting level height impacts surface precipitation phase and intensity. *Nature Climate Change*, **10**, 771-776, 10.1038/s41558-020-0825-x

Skamarock, W. C., Klemp, J. B., Dudhia, J., Gill, D. O., Liu, Z., Berner, J., Wang, W., Power, J. G., Duda, M. G., Barker, D. M., and Huang, X. -Y. (2019). *A Description of the Advanced Research WRF Model Version 4* (No. NCAR/TN-556+STR). doi:10.5065/1dfh-6p97.