Limited Literature Review on Warm Rain, Relevant to HIWC-2022

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What is warm rain?

- development of precipitation in the form of rain without the ice process
- Small droplets are created by nucleation on small aerosol particles, typically < 0.2 µm, during condensation in an updraft.
    - The condensation process tends to create narrowing droplet spectra with time. The time to create 50 µm diameter drops is exceedingly long, and it is generally accepted that the condensation process alone is unlikely to produce warm rain.
    - Collision and coalescence of drops following condensation process is required.
- The existence of a small number larger droplets, with fall velocities adequate to capture other smaller droplets in the population, is thought to initiate this “coalescence process” which can lead to warm rain
    - Commonly quoted that drops larger than about 40-50 µm diameter will quickly accelerate the warm rain process

Prevalence of warm rain

- Observations show that warm rain is common in tropical oceanic maritime clouds with tops warmer than the freezing level
- Rain has been observed to form on time scales of < 20 minutes
- Over the years, researchers have struggled to model the development of warm rain on such short time scales, and this has resulted in field campaigns and a multitude of modeling studies

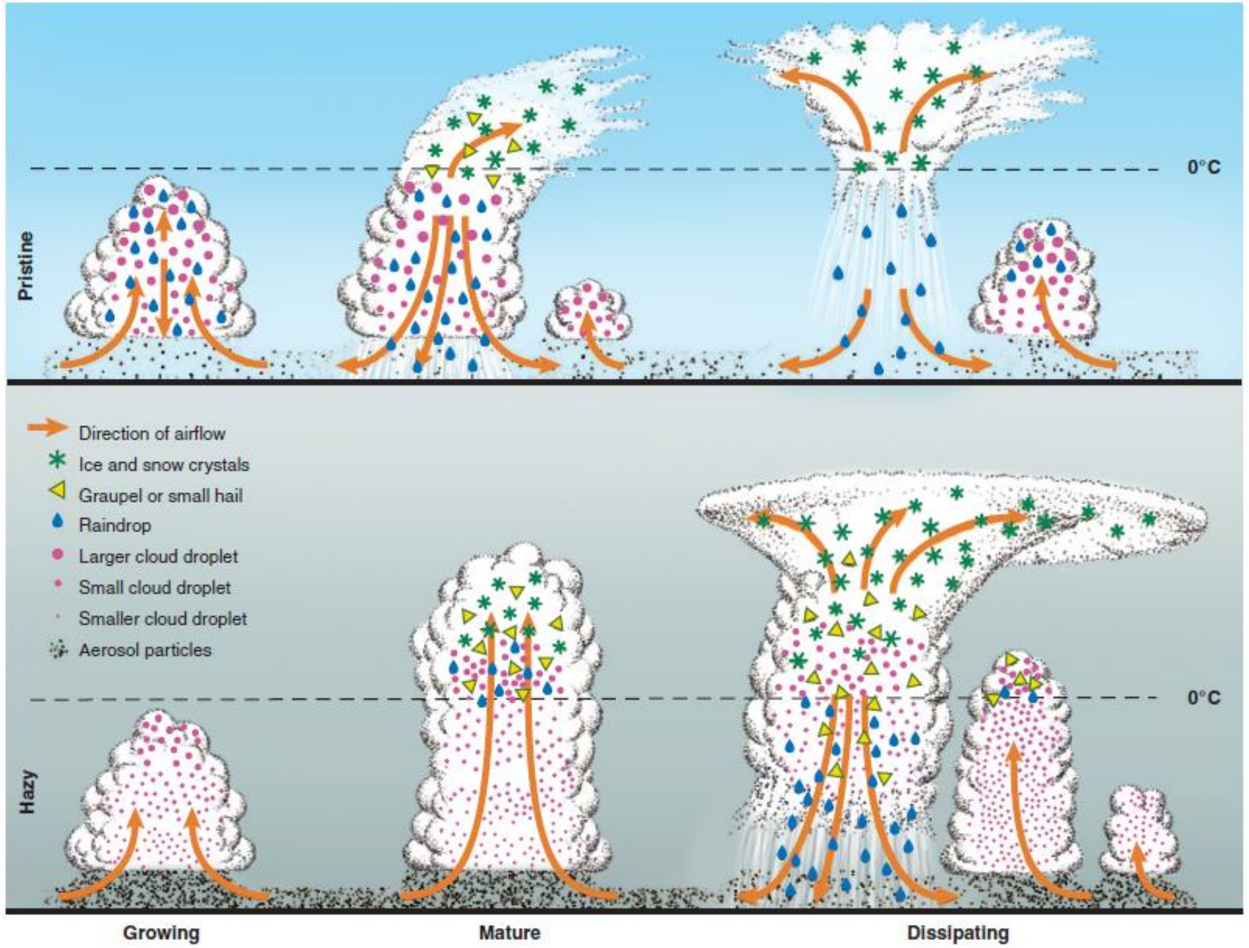
- Warm rain has also been reported in tropical continental convective clouds, for which aerosol properties are arguably quite different from maritime clouds (e.g. maritime have larger CCN, and lower CCN concentrations)

Why is warm rain important?

- It is a process that is fundamentally important for understanding of cloud physics and proper numerical simulation of clouds
  - Case in point is our current application to sensitivity studies of high IWC in a high aerosol environment

- For the world community, Global Climate Models attempt to predict the feedback of clouds on cloud radiation balance (i.e the effect on global temperature rises)
  - “Despite decades of research, it has proved frustratingly difficult to establish climatically meaningful relationships among the aerosol, clouds and precipitation. As a result, the climatic effect of the aerosol remains controversial” (Stevens and Feingold 2009, Nature Magazine)
  - “Precipitation parameterizations are a key source of uncertainty in GCMs, with positive bias to warm rain production relative to satellite observations. Different schemes far exceed uncertainty range of IPCC AR5, and cancel much of the warming trend of the last century”(Jing et al. 2019, J. Climate)

Why is warm rain important to HIWC-2022? Review of HIWC-2022 first order hypothesis



From Rosenfeld et al. 2008

- Polluted clouds nucleate smaller drops, and warm rain is suppressed
- In heavy forest fire smoke cases, warm rain can be practically shut off (Rosenfeld, 1999)
- Pollution delays the precipitation of cloud water, ***so that more water can ascend to altitudes where the temperature is colder than 0 C*** (Rosenfeld et al. 2008)

- Additional cloud water that eventually freezes releases latent heat of fusion and re-invigorates instability and leads to higher and longer lasting clouds

- **We are therefore looking for evidence of warm rain suppression in the HIWC-2022 dataset.**

Theories for acceleration of warm rain (early production of large drops)

Classical calculations of condensation growth coupled with coalescence – collection, including random effects (stochastic coalescence) have been unable to produce warm rain on 20 minute time scales. In order to accelerate the process, the following processes have been proposed:

- turbulent enhancement of drop collisions (e.g. Shaw 1998)
- cloud entrainment and mixing
  - Entrainment reduces drop concentration, enhancing subsequent growth of fewer drops (Baker, 1980)
- Giant aerosol nuclei (GCCN, 0.2 – 2.0 µm dia.) and Ultra Giant nuclei (UGCCN, ≥ 20 µm dia.)
  - "Big aerosol make big drops" (e.g. Johnson, 1982)
  - For maritime clouds, sea salt is a likely source, even up to 200 µm diameter (Woodcock, 1953)
- Several other processes have been postulated but have not been pursued in the literature (e.g. electrical effects)

Renewed interest in solving the warm rain problem through the 1990s and 2000s. Research Projects.

- The **Joint Hawaiian Warm Rain Project (JHWRP)** **,** 1985, followed by the
- The **Hawaii Rainfall Project (HaRP),** 1990.
  - Articles from these projects have focussed on the observation of giant raindrops 4-8 mm dia., which are predicted to not exist due to drop breakup from collisions.
  - For our HIWC-2022 problem, there is no discussion of high concentration aerosol effects, or a specific focus on the time required of warm rain initiation.

Renewed interest in solving the warm rain problem through the 1990s and 2000s. Research Projects.

- The **Small Cumulus Microphysics Study (SCMS)** , 1995, Florida
- The **Rain In shallow Cumulus over the Ocean (RICO)** project, 2004-2005, Aruba, Barbuda, Rauber et al. 2007.
  - Both projects studied warm-topped cumulus with in-situ aircraft measurements and sensitive ground based radar
  - SCMS focussed on following individual clouds, RICO sampled multiple clouds in a more statistical approach
  - Spawned many articles from the experiments themselves, and other independent research not directly linked to the campaigns
- The **Cloud Aerosol Interaction and Precipitation Enhancement Experiment (CAIPEEX)** Kulkarni et al. 2012
  - Multi-objective campaign organized by Indian Institute of Tropical Meteorology
  - Includes aircraft measurements of TCu in clean and polluted atmospheres in 2009, 2010, more extensive than ours (special interest to HIWC-2022)
- The DLR **ACRIDICON-CHUVA** 2014campaign:
  - Aerosol, Cloud, Precipitation, and Radiation Interactions and Dynamics of Convective Cloud Systems- Cloud Processes of the Main Precipitation Systems in Brazil
  - Studying tropical deep convective clouds and precipitation over continental and Amazonia using the new German research aircraft HALO.
  - Includes in-situ measurements mostly in polluted and pristine continental TCu clouds.
- Several other projects related to <u>stratus</u> and <u>stratocumulus</u> not detailed here

List of articles considered

Article	year	data	model	cloud type	Comments
Ochs and Semonin	1979		Closed parcel model	unclear	CCN between 10 and 80 um are important in determining first echo height in continental clouds
Feingold et al.	1999	ASTEX	multiple models	Scu	UGN increased drizzle when CDC high, less so when low
Khain et al.	2000				GN have relatively weak effect on large drop formation.
Hudson and Yam	2001	SCMS	Observations	warm marine Cu	Effect of CCN dominates over GCCN
Rosenfeld et al.	2002		only abstract reviewed	n/a	Pollution strongly suppresses precip over land, less so over water due to sea salt
Blyth et al.	2003	SCMS	Closed parcel stochastic coalescence model	warm marine Cu	Coalescence growth of GCCN and UGCCN sufficient to explain SCMS observations
Lu and Seinfeld	2005		Regional Atmospheric Modeling System (RAMS) LES	marine Scu	Impacted when CCN > 1000 cm-3
Teller and Levin	2006		Tel Aviv U. 2D cloud model with detailed treatment of cloud microphysics.	deep convective mixed-phase	GCCN enhance precipitation for high aerosol cases, but little effect for low CCN
Zhang et al.	2006		LES	warm stratiform	ambient GCCN concs. ~ 3 cm-3 inhibit rain production. 60 cm3 increases rain production.
Goke et al.	2007	SCMS	Radar observations	warm marine Cu	precipitation development in the SCMS clouds was primarily controlled by CCN concentrations rather GCCN concentrations
Jensen and Lee	2008		adiabatic stochastic Monte Carlo cloud model	marine Scu	SiGCCNificant effect of GCCN, mixing and turbulence enhancements only minor
Cheng et al.	2009	RICO	Regional Atmospheric Modeling System (RAMS) LES	warm trade wind Cu	GCCN had a larg effect under high CCN conditions
Khain et al.	2009	CAIPEEX		maritime and continental Tcu	Discussion about the development of presip in Indian clouds and importance of high LWC adiabatic zones and mixing zones. Processes duiscussed.
Lowenstein et al.	2010	RICO	only abstract reviewed; condensation and stochastic coalescence model, run in the framework of a closed parcel	marine Cu	large-size tail of the observed DSDs can be explained with the observed sub-cloud particles, including giant and ultra-giant aerosols, includes FSSP and 2D-S
Reiche and Lasher Trapp	2010	RICO		warm trade wind Cu	other factors more important than GCCN in first radar echo. Cloud depth most important factor.
Kogan et al.	2012	RICO	CIMMS large-eddy simulation (LES)	shallow Cu	Under clean conditions, GCCN of 1.5 cm-3 increased precip by 30%. the effect of the larger nuclei to enhance the precipitation predominates, and accumulated precipitation increases with wind speed.
Gerber H. and G. Frick	2012	RICO	lagrangian	warm trade wind Cu	GCCN important only for high CCN.
Konwar et al.	2013	CAIPEEX	Observations only	Cu, Tcu	CCN affected height of warm rain. GCCN quite important for very high conc. Continental. Secondary importance for low CCN.
Blythe et al.	2013	RICO	MAC3 bin-resolved, dual-moment(i.e. mass and number) cloud model. Binned microphysics.	warm trade wind Cu	condensation and stochastic coalescence alonequickly produced rain. Eliminating GCCN and UGCCN did not affect results, even in high CCN testing. Postulated on role of high LWC.
Dagan et al.	2015		Axisymmetrical single-cloud model with bin microphysics		GCCN shortens delay in coalescence initiation. Can turn a non-precipitation polluted cloud into a precipitating on. Effect even at background. Varied CCN greatly.
Jensen and Nugent	2017		adiabatic stochastic Monte Carlo cloud model	Scu	GCCN increased rainfal for GCCN ~ 0.3 cm-3. GCCN larger than 2 um account for most of rainfall. Large CCN remain solution drops and attain higher SSs
Braga et al.	2017	ACRIDICON	Observations	maritime and continental Tcu	Continental cloud observations in polluted and non-polluted atmospheres. Evidence of warm rain suppression in polluted clouds.
Konwar et al.	2017	CAIPEEX	Observations	maritime and continental Tcu	Warm rain shifted to higher altitudes win increasing CCN. Quasi complete warm rain shudown over continent
Dziekan et al.	2021	RICO	LES model with Lagrangian cloud microphysics	warm trade wind Cu	Simulations at 38, 60, and 88 cm-3. GCCN significantly increase precipitation in stratocumuli, smaller impact on cumuli.

Issues related to summarizing literature

- Mesmerizing combination of cloud types, aerosol levels, numerical model types and sophistication of models and observations
- It is difficult to determine whether studies actually show warm rain within 20 minutes: favoured metric is the height above cloud base for first radar echoes
- Since HIWC-2022 TCu studies will show that warm rain had developed in all clouds sampled (evidence to come), and droplet embryos of ~ 50 µm were present in all cloud base runs, HIWC-2022 has a natural interest in the role of giant and ultra-giant CCN since sea-salt was suspected to be present.
- Approach
  - Document articles that support CCN effects on warm rain, those identifying GCCN as important, and look for articles that identify other features that seemed to be also present in HIWC-2022.
  - Summarize common themes (in a subjective manner)
  - confusing

Articles confirming the effect of increasing CCN, in delaying warm rain

Models:

- Feingold et al. (1999), Yin et al. (2000), Rosenfeld et al. (2002), Lu and Seinfeld(2005), Teller and Levin (2006), Jensen and Lee (2008), Cheng et al. (2009) , Dagan et al. (2015).

Observations:

- Konwar et al. (2013, 2017), Braga et al. (2017), Hudson and Yum (2001)

- There is a general claim that higher CCN concentrations increases the height at which warm rain is first observed, or that drizzle is suppressed by high CCN

- I found no articles that contradicted this effect, so the conclusion that increasing CCN concentrations detrimentally affect warm rain seems sound.

Articles claiming or showing that high CCN concentrations can completely suppress warm rain

Models:

- Did not find one that explicitly tested this, or drew any specific conclusions in this regard

Observations:

- Rosenfeld et al. (1999)
- Konwar et al. (2017), and Braga et al. (2018)
  - These aircraft TCu observations are particularly interesting, and will be compared to our HIWC-2022 measurements in later slides

Articles claiming that the existence of giant CCN (e.g. sea salt) was important to warm rain

Models:

Of primary importance:

- Ochs and Semonin (1979), Johnson (1982), Beard and Ochs(1993), Szumowski et al. (1999), Lasher-Trapp et al. (2001), Rosenfeld et al. (2002), Blythe et al. (2003), Jensen and Lee (2008), Cheng et al. (2009), Lowenstein et al. (2010), Kogan et al. (2012),Cooper et al. (2013), Dagan et al. (2015), Jensen and Lee (2017)

Important only at high CCN concentrations:

- Feingold et al. (1999), Yin et al. (2000) , Hudson and Yum (2001), Lu and Seinfeld (2005), Teller and Levin (2006), Gerber and Frick(2012),

Observations (limited articles):

Of primary importance: none

Important only at high CCN concentrations:

Konwar et al. (2013, 2017),

Articles claiming GCCN of minor/no importance to warm rain development

Models:

- Khain et al. (2000), Zhang et al. (2006), Goke et al. (2007), Reiche and Lasher-Trapp (2010), Blythe et al. (2013), Dziekan et al. (2021)

Observations:

- Braga et al. (2018), not discussed in detail, but the absence of a discussion seems to indicate unimportance

Note that both Blythe and Lasher-Trapp have earlier articles declaring the importance of GCCN

Articles noting the importance of high LWC in warm rain development

- Szumowski et al. (1999), Khain et al. (2009), Cooper et al. (2013), Blythe et al. (2013)

- Blythe et al. (2013) contend that large drops can form by condensation and coalescence alone from the main mode of the drop spectra if remaining in high LWC zones. These authors point out that this importance of high LWC was previously pointed out by Twomey (1966)

Articles noting amount of increase of LWC at altitude when warm rain is suppressed

- NONE

Strapp conclusions

From the preponderance of results in the literature, it seems reasonable to conclude

1. Increasing CCN concentrations delay the onset of warm rain, or cause it to first appear at a higher altitude in cloud
2. Giant CCN (GCCN) may enhance warm rain, but most articles suggest that GCCN are important to warm rain only when CCN concentrations are high.
3. The initiation of warm rain requires drop spectra to reach a critical spectral size
   - Old articles say require 40-50 µm diameter droplets
   - Newer articles specify values of effective radius of 11-15 µm [Braga et al. 13-14 µm; Khain et al. 15 µm (clean) to 10-11 µm (polluted)]
4. There is no definitive conclusion as to under what conditions warm rain can form in less than 20 minutes
   - The interest has shifted more to how aerosol affects clouds and thus climate
   - The discussion about high LWC in cloud being an accelerating effect seems eminently reasonable, and high LWC is certainly observed in our HIWC-2022 TCus.

Strapp conclusions (cntd)

5. There are two articles that contain TCu observations similar to those of HIWC-2022, but covering higher aerosol regimes. Some results are similar to those of HIWC-2022.
    - CAIPEEX (India) and ACRIDICON (Brazil) both document complete warm rain suppression past the freezing level for continental high aerosol cases (no such measurements in HIWC-2022)
    - We can possibly use these studies to compare and extend the results of our HIWC-2022 TCu experiments.
6. There are no model or observational assessments of the effect of high aerosol on LWC or TWC above the freezing level. This question is not of primary interest in the cloud physics literature, and remains open.

End of presentation