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Stochastic machine learning for atmospheric fields with generative adversarial networks

Jussi Leinonen

With contributions from Alexis Berne (EPFL), Daniele Nerini (MeteoSwiss), Tianle Yuan (NASA-GSFC/UMBC), Alexandre Guillaume (NASA-JPL)

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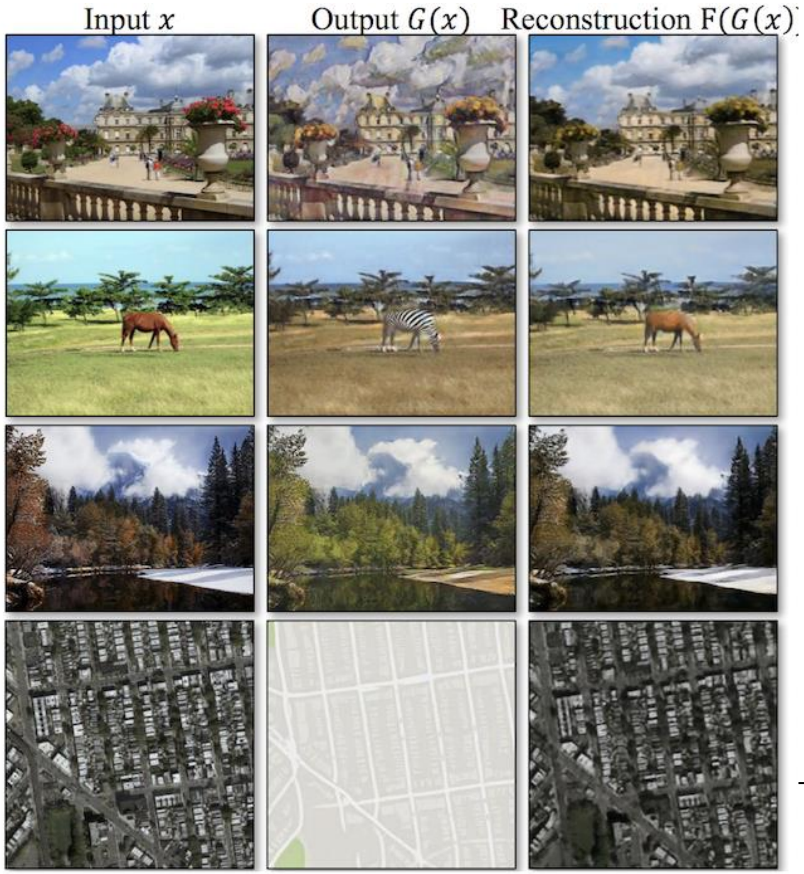
Generative adversarial networks (GANs)

Example applications:

Image generation

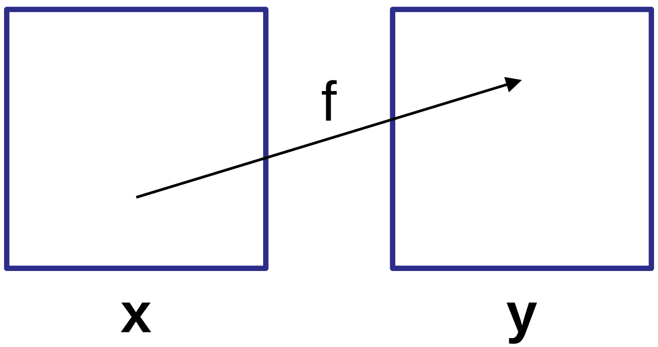
Domain translation



Infilling

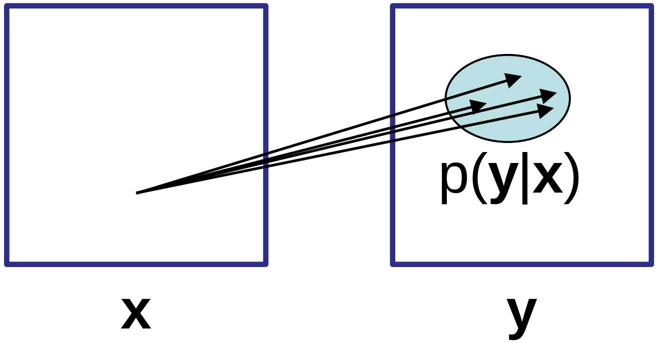
Generative models

- Typical predictive model:
  predict **y** = f(**x**)
  - One answer per input



- Generative model:
  generate samples from p(**x**)

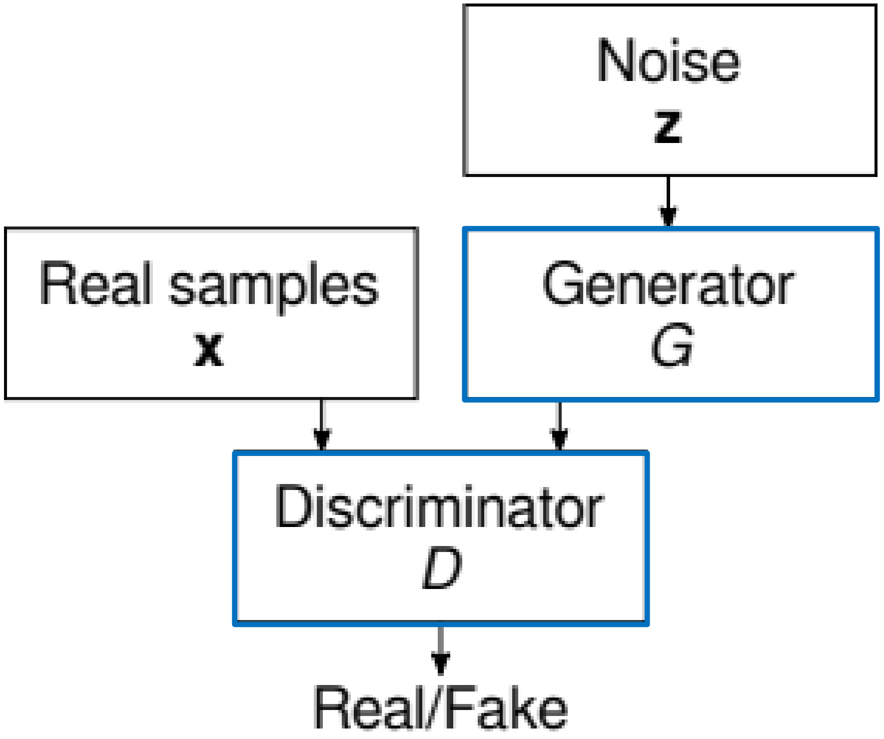
- Conditional generative model:
  generate samples from p(**y**|**x**)
  - Multiple answers per input,
    uncertainty modeled



Generative adversarial networks (GANs)

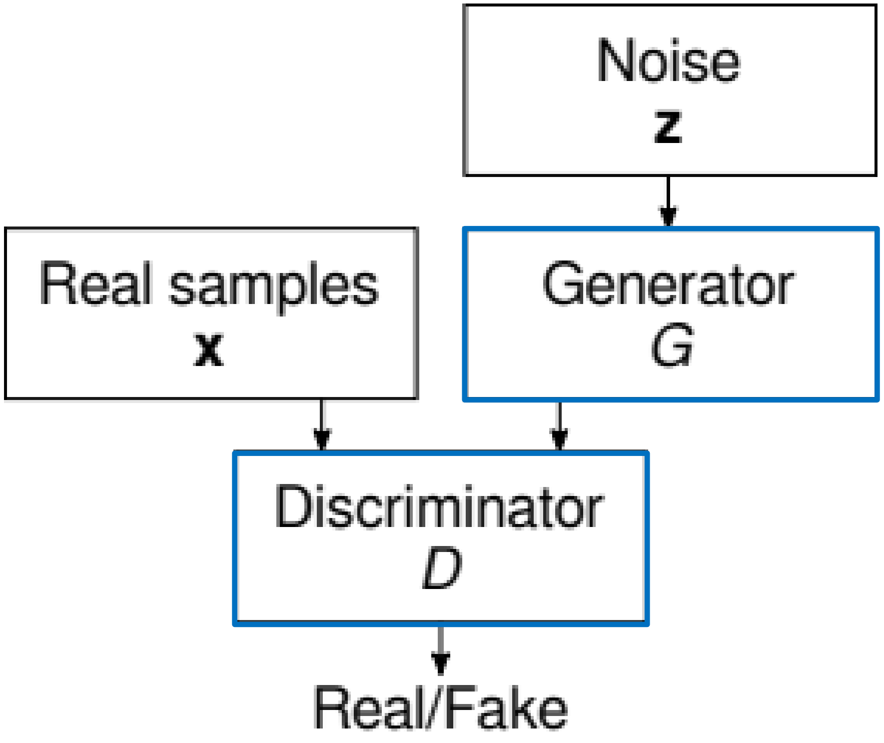
Two competing (usually convolutional) neural networks:

- Discriminator tries to distinguish real samples from generated ones
  - CNNs are powerful image classifiers
- Generator tries to output samples that discriminator considers real
  - ➢ Leans to generate realistic samples



Generative adversarial networks (GANs)

GAN generator: map
p(**z**) → p(**x**)

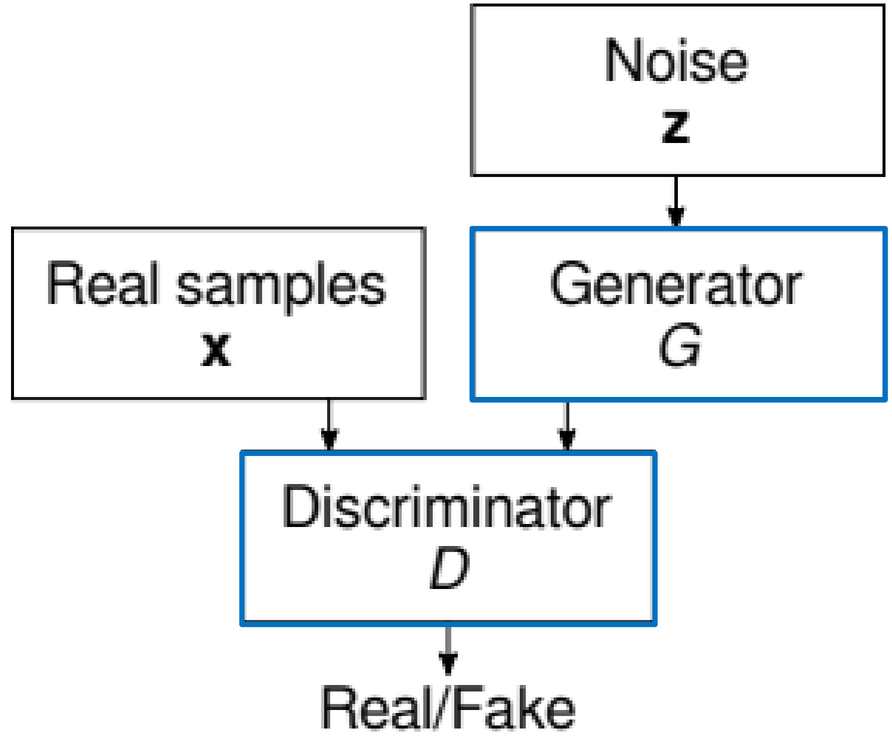


Generative adversarial networks (GANs)

GAN generator: map p(**z**) → p(**x**)

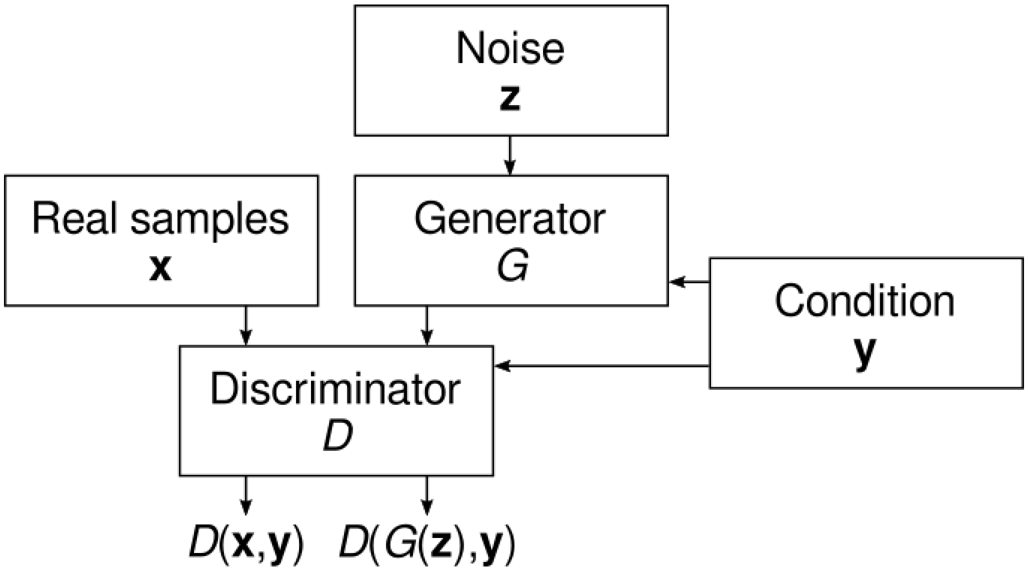
Simple

Complex, spatially correlated



Conditional GANs

CGAN generator: map
p(**z**,**y**) → p(**x**|**y**)



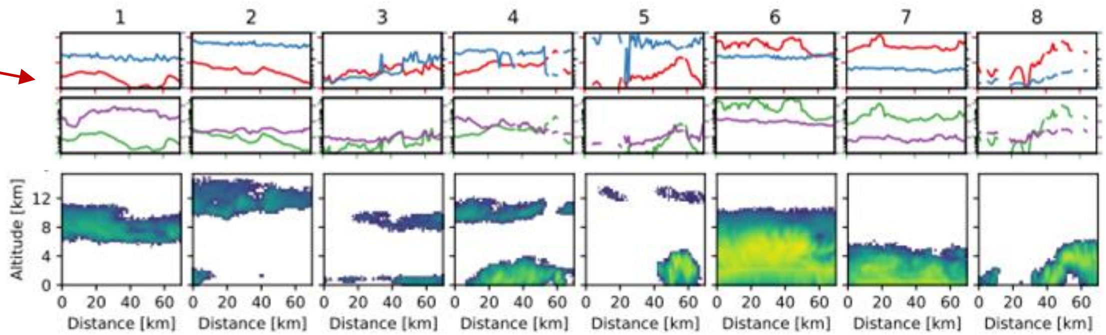
Conditional probability problems

- Ubiquitous in Atmospheric and Climate Sciences
- Examples: inferring...
  - p(Quantity x | quantities y)
  - p(Quantity x | measurements y)
  - p(Future state | current and/or past state)
  - p(High resolution field | low resolution field)
  - p(Complete data | incomplete data)
- Underdetermined problems, CGANs can learn to generate the conditional *distribution* of solutions
  - ➢ Uncertainty modeled

Generating cloud profiles with CGAN

Dataset of collocated cloud observations from:

- MODIS spectrometer (1D, 4 variables)
- CloudSat radar (2D, 1 variable)



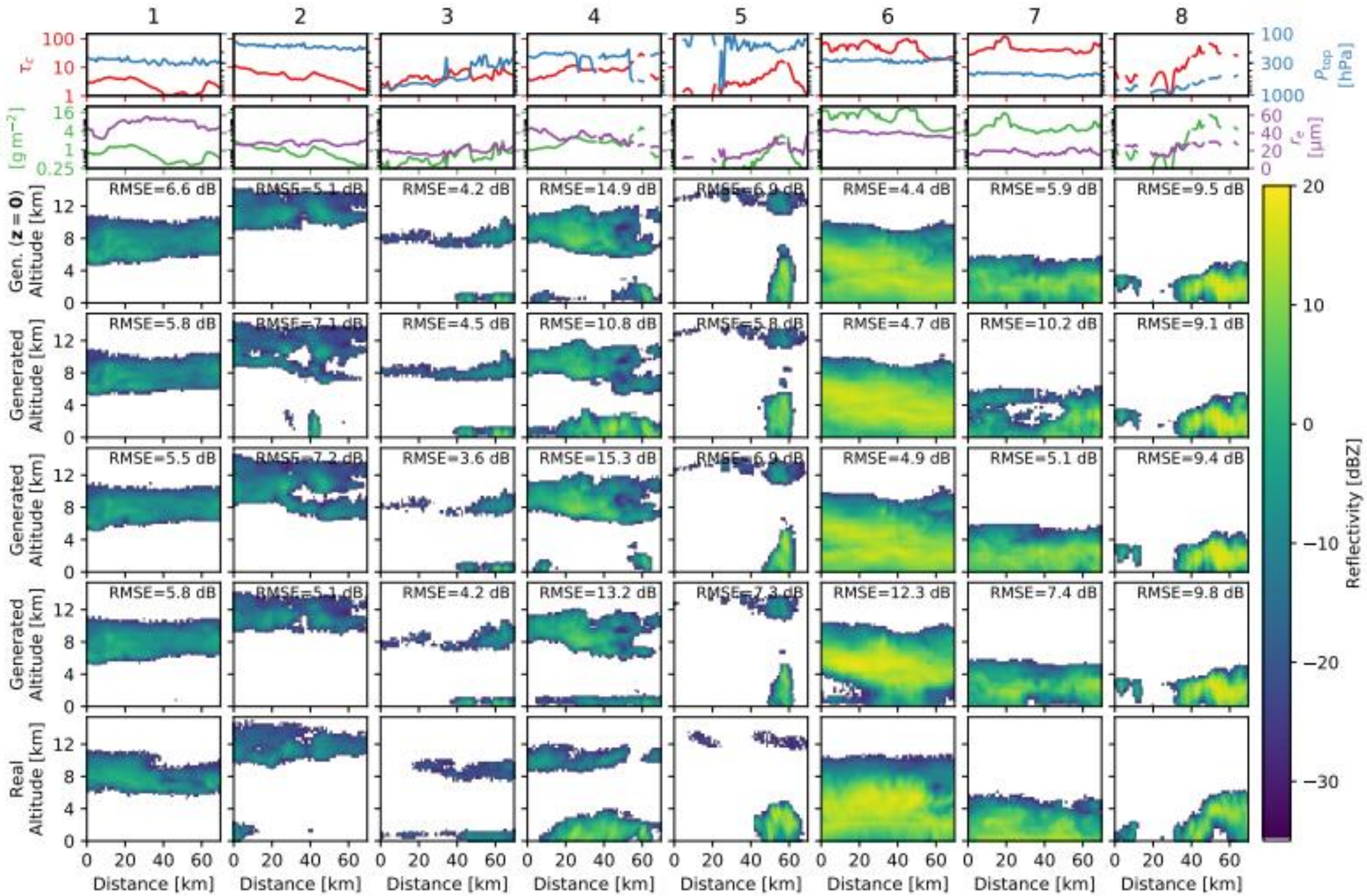
Can we train a CGAN to generate the CloudSat vertical profiles based on the MODIS data?

Generating cloud profiles with CGAN

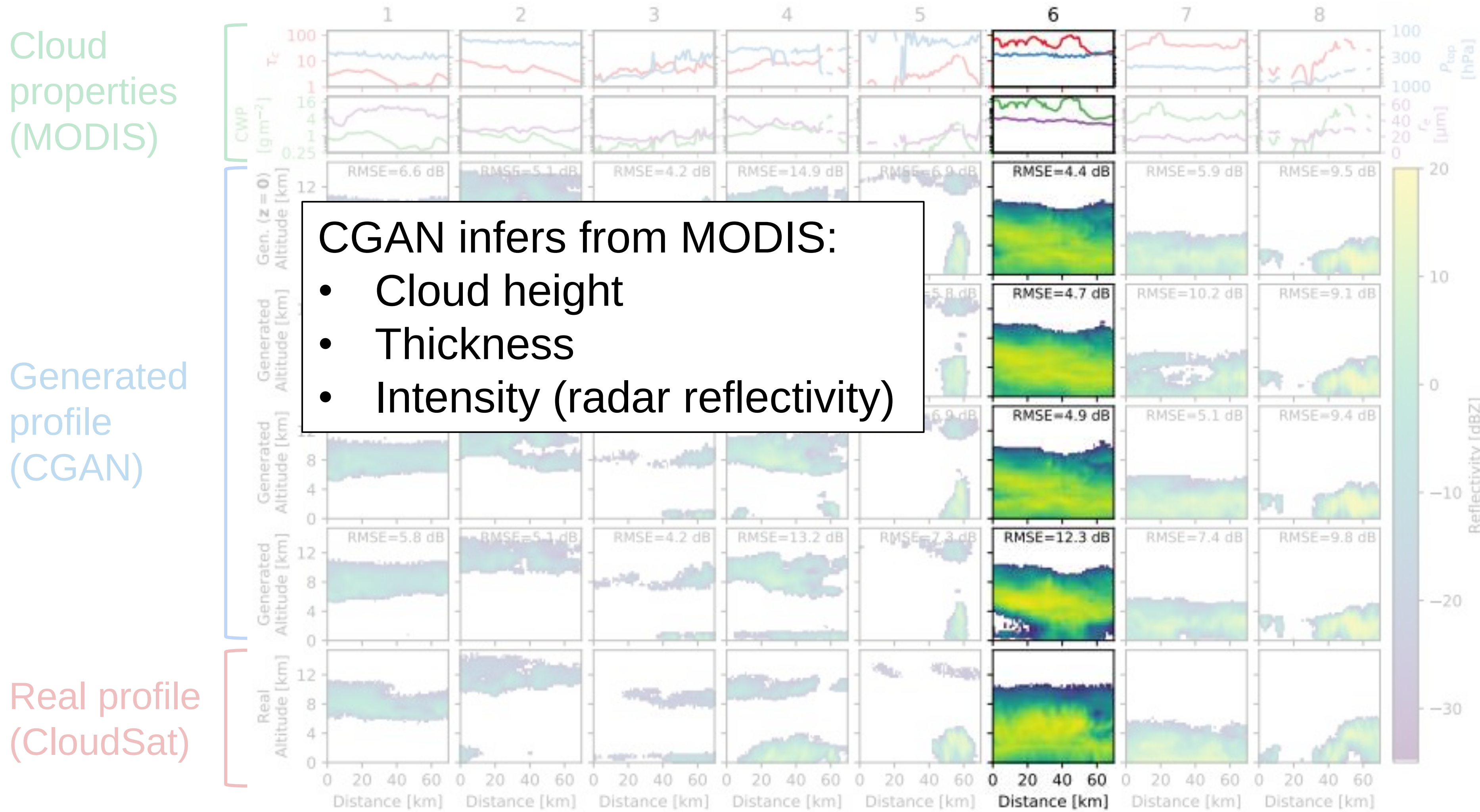
Cloud properties (MODIS)

Generated profile (CGAN)

Real profile (CloudSat)



Generating cloud profiles with CGAN

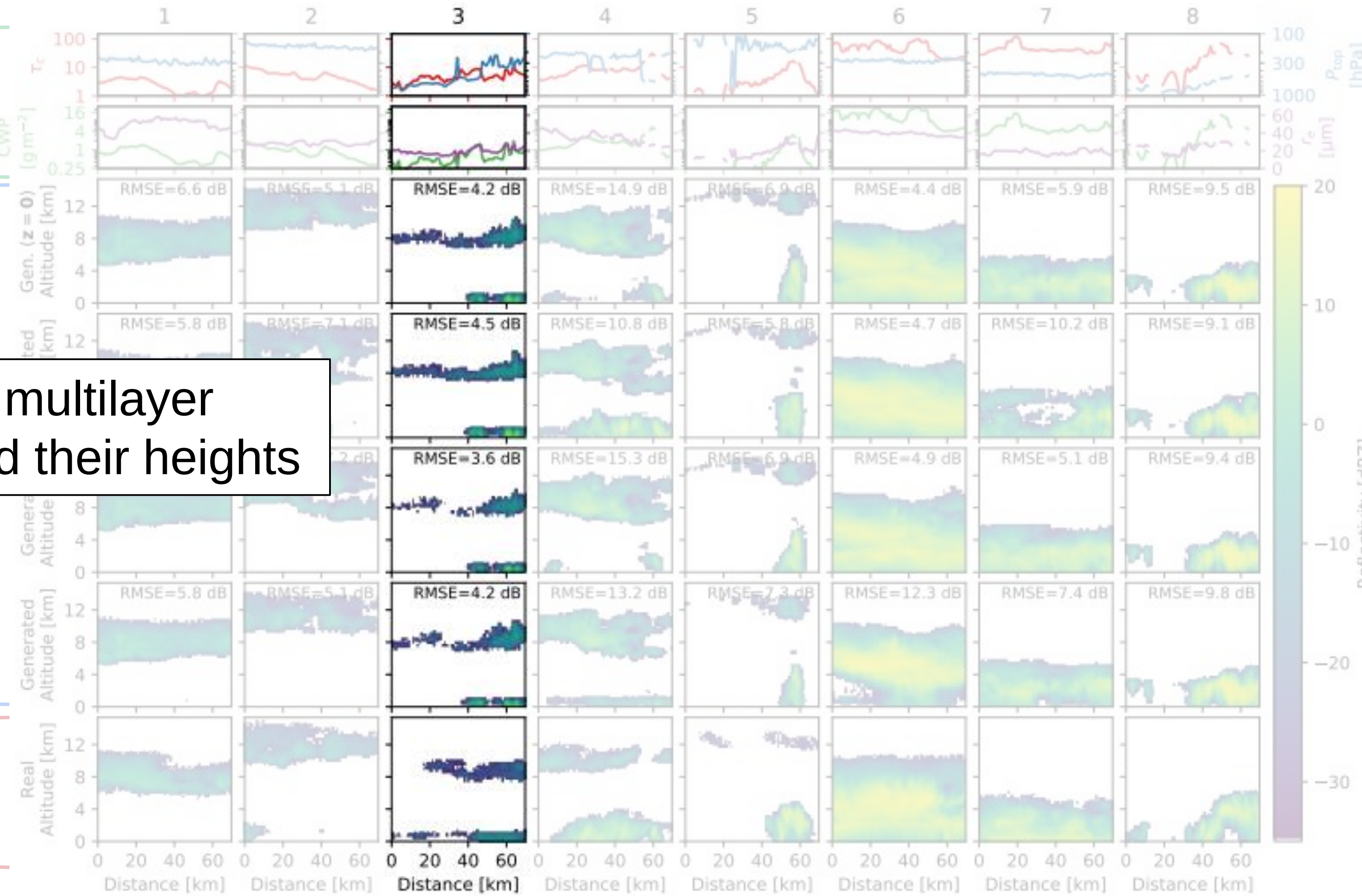


CGAN infers from MODIS:

- Cloud height
- Thickness
- Intensity (radar reflectivity)

Generating cloud profiles with CGAN

Cloud properties (MODIS)



Generated profiles (CGAN)

Detecting multilayer clouds and their heights

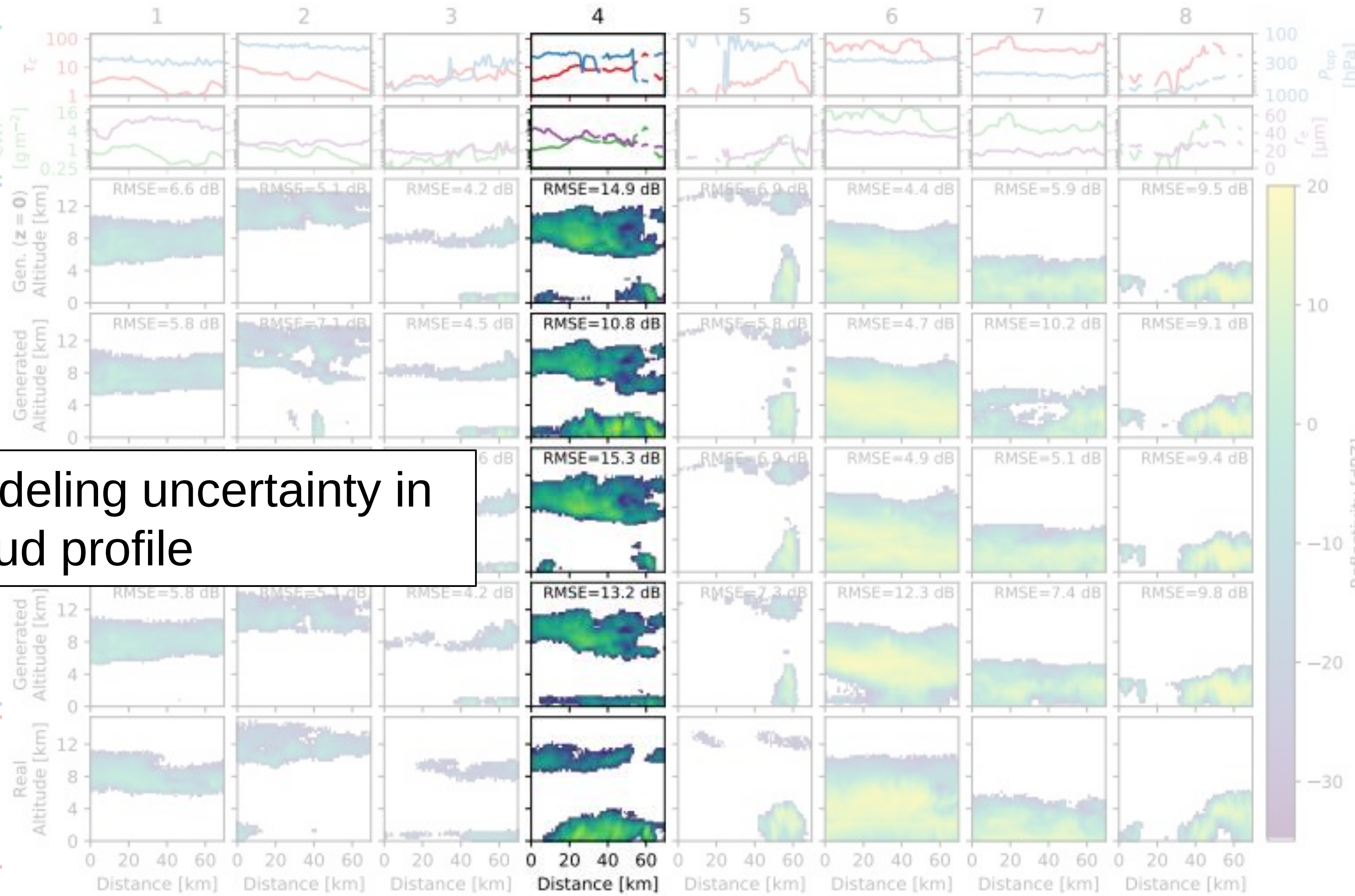
Real profile (CloudSat)

Generating cloud profiles with CGAN

Cloud properties (MODIS)

Generated profile (CGAN)

Real profile (CloudSat)



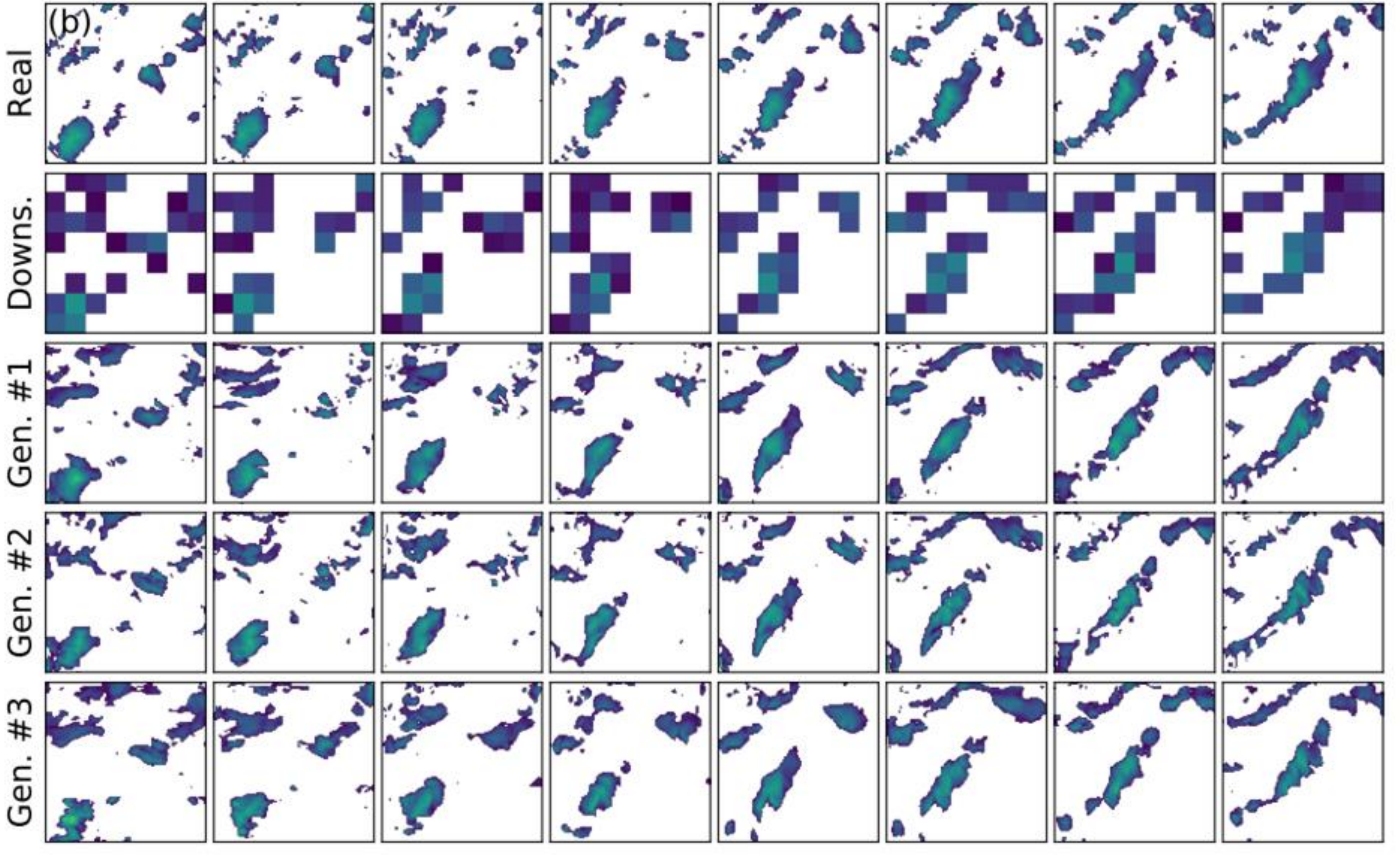
Modeling uncertainty in cloud profile

Stochastic downscaling of precipitation data

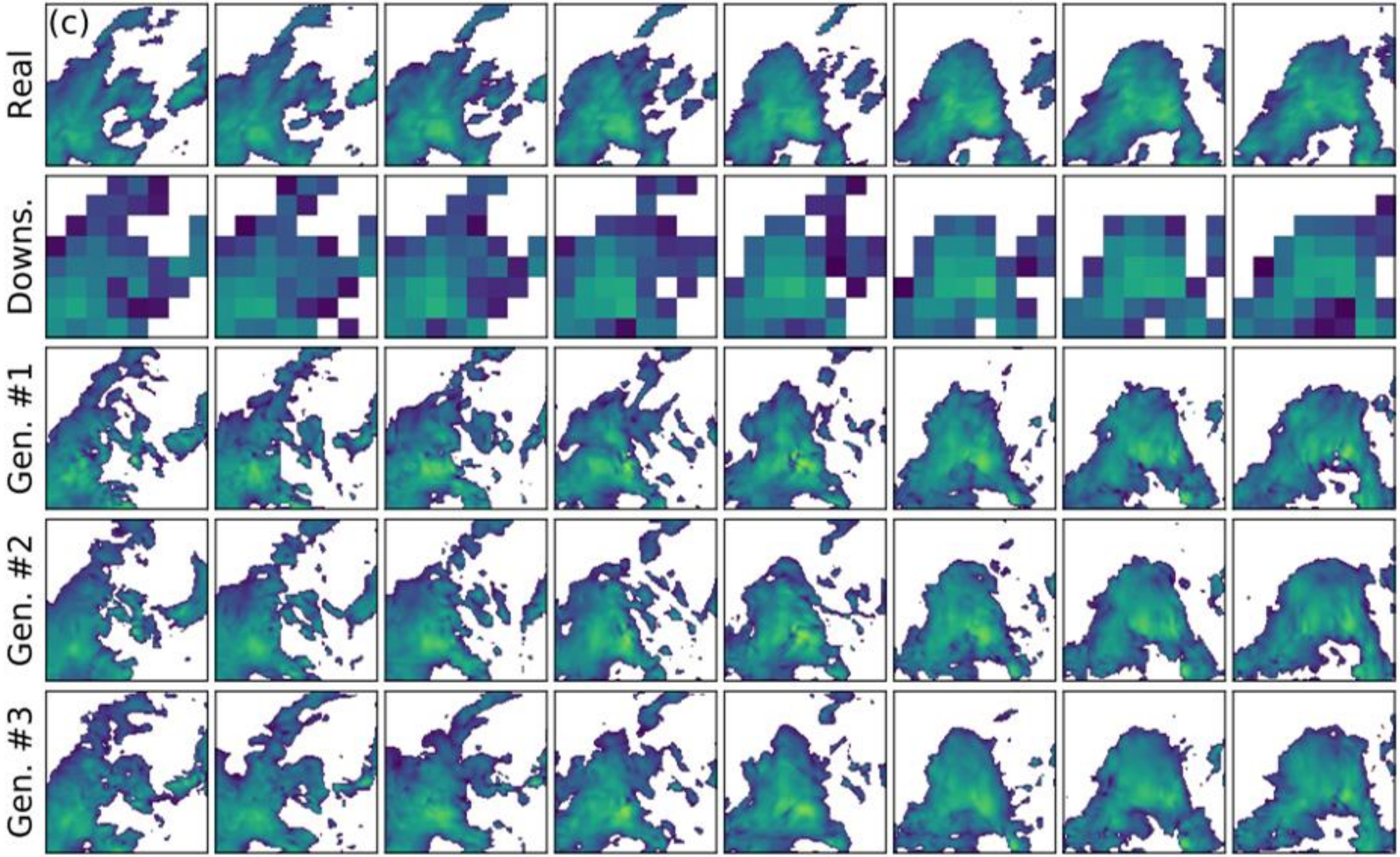
- Objectives:
  - Demonstrate stochastic downscaling with GANs (i.e., generate high-resolution fields from low-resolution inputs)
  - Generate realistic fields
  - Use the non-deterministic aspect of GANs to model the uncertainty
  - Model the time evolution of fields consistently
    - ➢ We need a recurrent generator

Stochastic downscaling of precipitation data

Leinonen et al. 2020

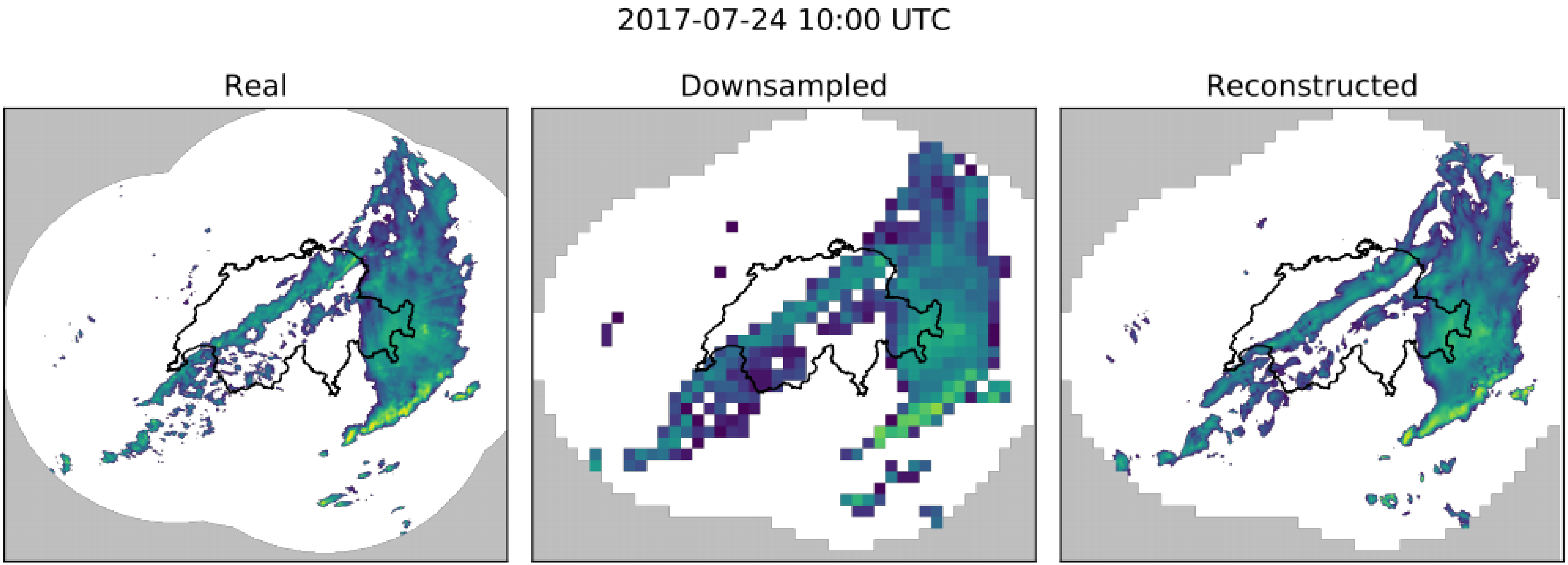


Stochastic downscaling of precipitation data



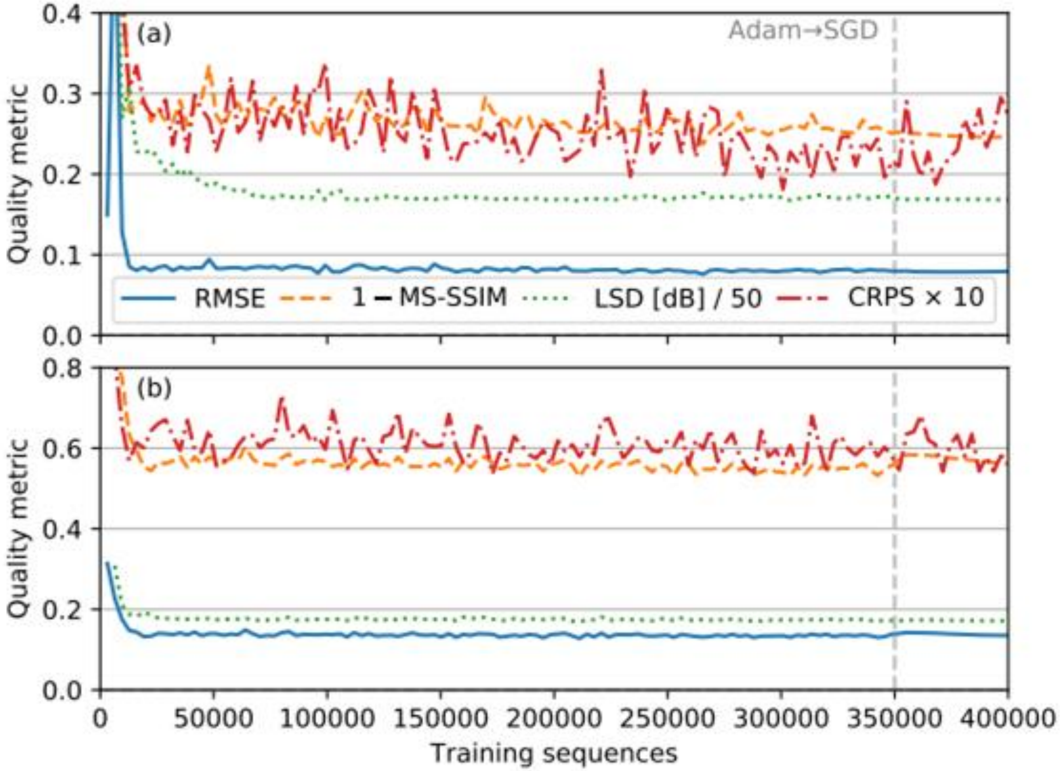
Stochastic downscaling of precipitation data

Fully convolutional generator:
can be applied to larger images after training



Evaluation: Image quality metrics

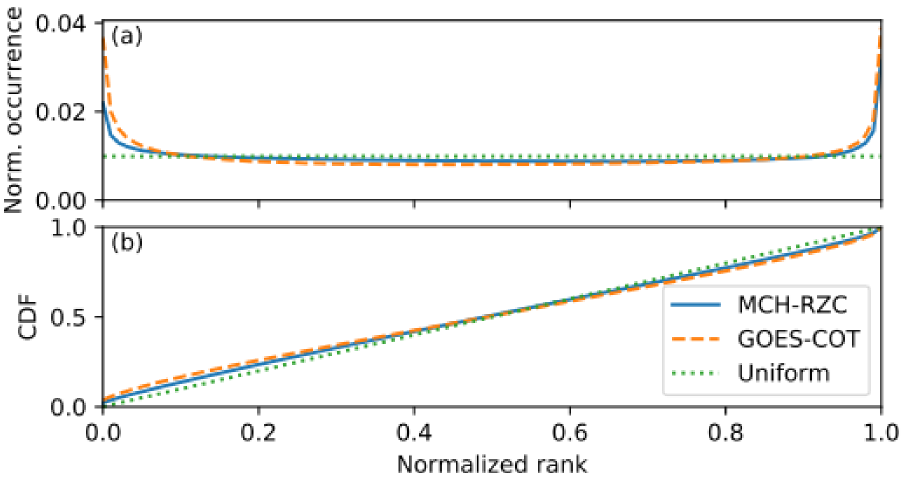
- Single-image quality metrics don't tell us very much
  - GAN isn't trained to optimize them
- CRPS is an ensemble metric that uses multiple predictions, works better



Rank statistics

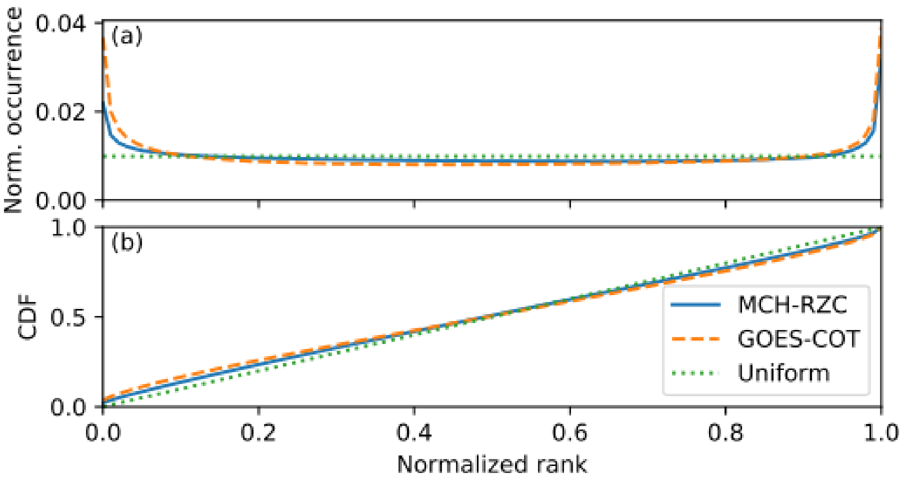
Does the distribution of values generated by the GAN match that of the observations?

- We don't know the true conditional distribution



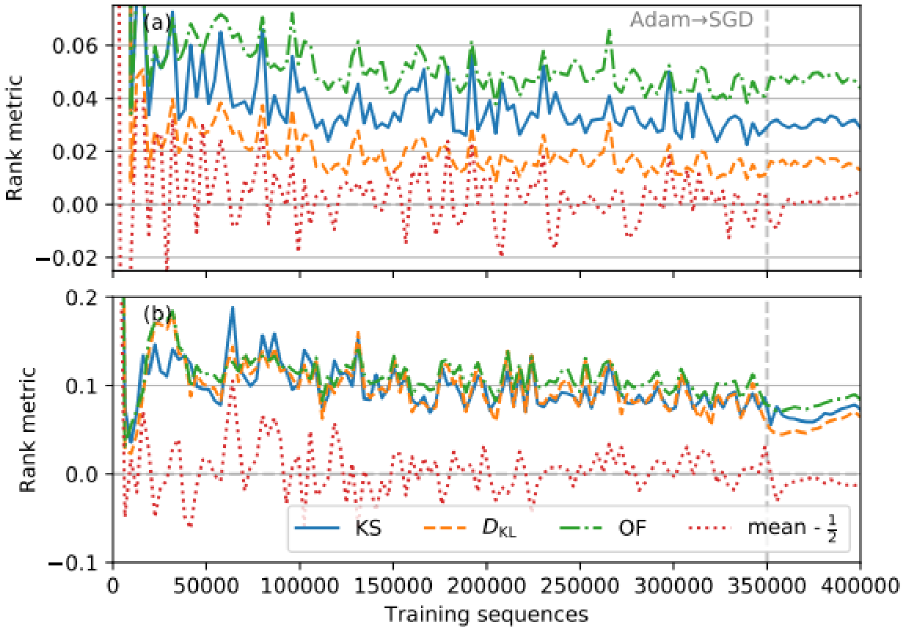
Rank statistics

- Compute the *rank* of the real observation in the ensemble, normalize to 0..1
- If uncertainty is modeled perfectly, the rank should be *uniformly distributed*
  - We can use metrics of similarity to the uniform distribution to evaluate whether the GAN is generating the right amount of uncertainty



Rank statistics

- Rank metrics converge for longer than image quality metrics



Other studies using GANs

- Snowflake classification
- Rainfall disaggregation
- Generating global climate data fields
- Downscaling of global climate model data
- Nowcasting radar time series

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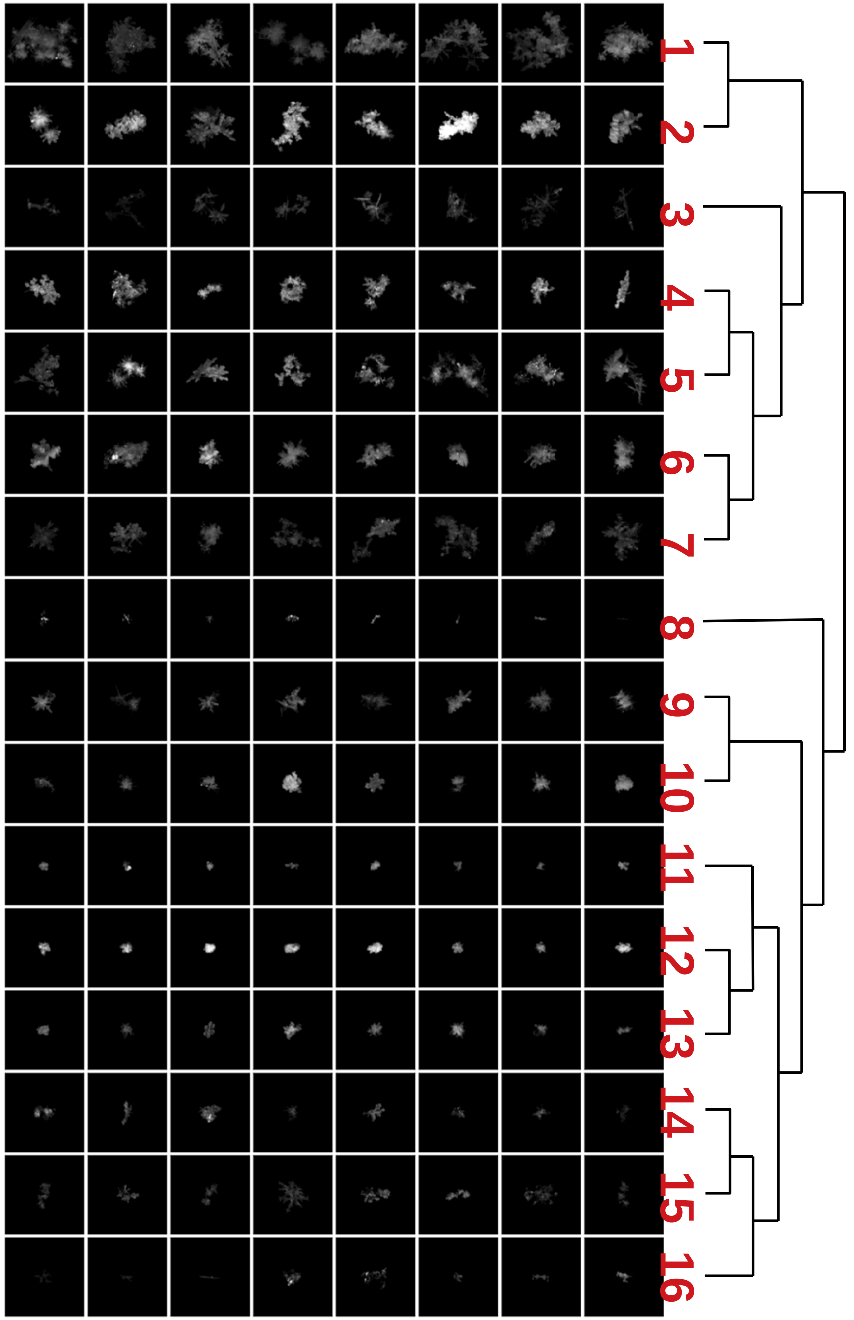

Leinonen et al. 2020, AMT
https://doi.org/10.5194/amt-13-2949-2020

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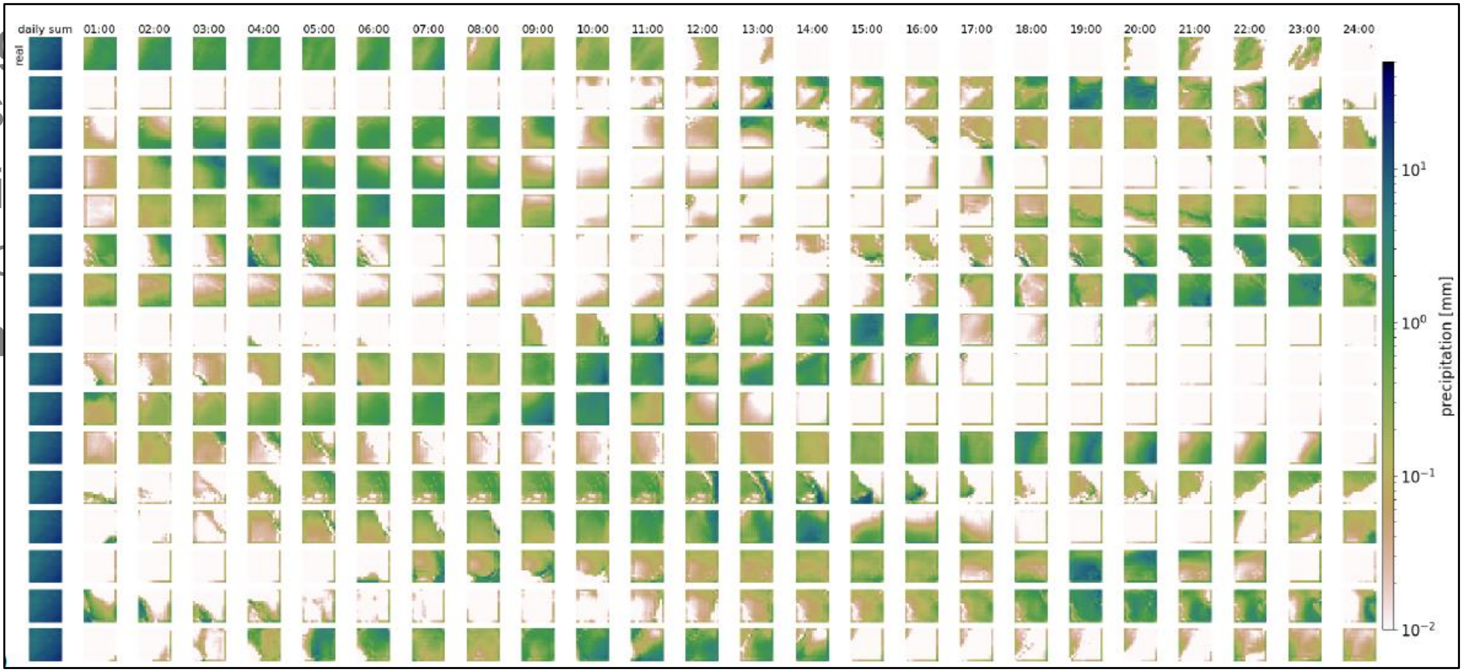

Scher and Peßenteiner 2021, HESS
https://doi.org/10.5194/hess-2020-464

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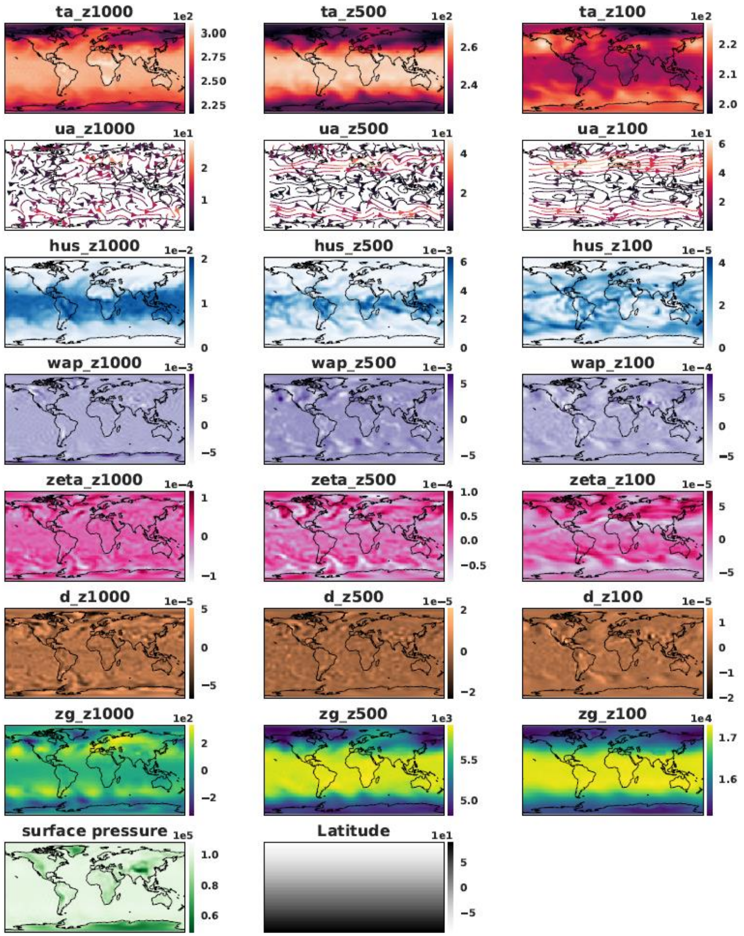

Besombes et al. 2020, NPG
https://doi.org/10.5194/npg-2021-6

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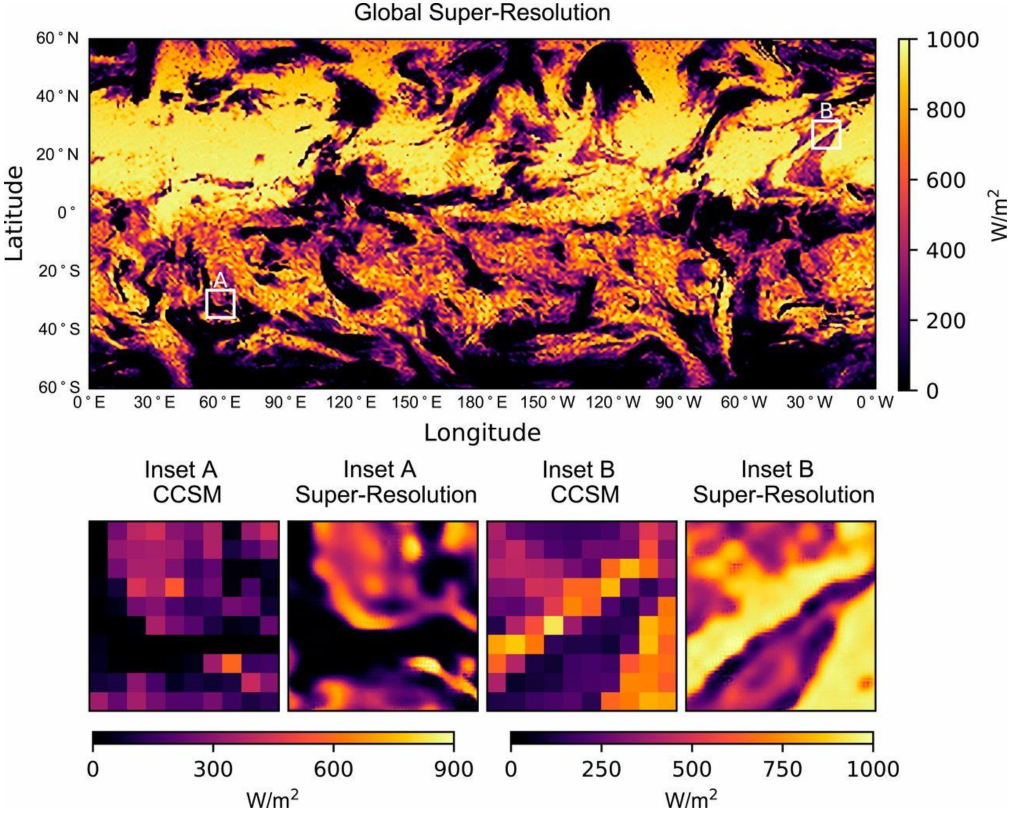

Stengel et al. 2020, PNAS
https://doi.org/10.1073/pnas.1918964117

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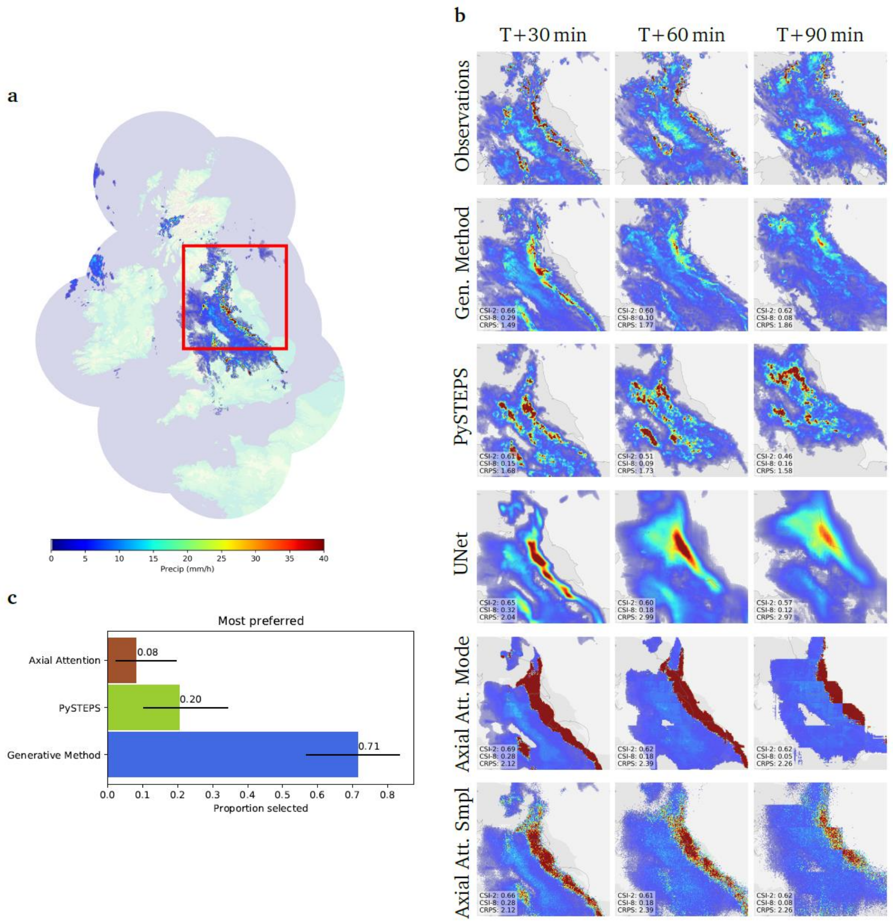
- **Nowcasting radar time series**

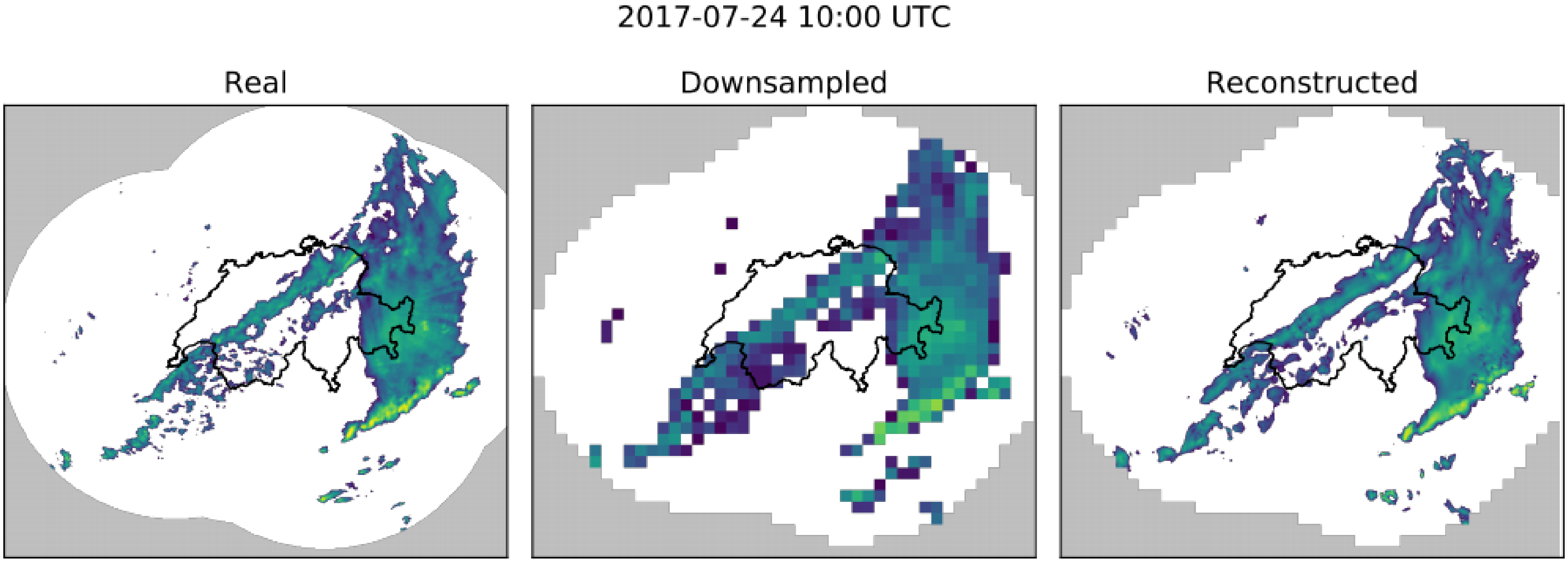


Ravuri et al. 2021
https://arxiv.org/abs/2104.00954

“Should I consider GANs for my project?”

- GANs (and CGANs in particular) seem a natural fit for many Earth science data problems
  - Consider CGANs if you need realistic spatial structure and/or uncertainty modeling
  - GANs can also do unsupervised data discovery
  - Many low-hanging fruits still available to pick!
  - But tricky to work with, needs cost-benefit evaluation
- GANs model uncertainty through sample diversity
  - Ensemble forecasters have the same mindset
  - Methods from ensemble forecasting can be applied to GANs

Questions?



https://www.youtube.com/watch?v=3OS6hz8gYC8