Development of a Polarimetric Radar Forward Operator for the Bayesian Observationally Constrained Statistical-physical Scheme (BOSS)

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Introduction

- We are developing a novel warm-rain microphysics scheme (BOSS, ***Poster 119***).
- BOSS uses Bayesian inference for robust parameter uncertainty estimation, which facilitates constraint by observations.
- Dual-polarization radar observations will provide a probabilistic constraint on scheme structure and microphysical sensitivities to environmental conditions.
- BOSS can use any combination of prognostic drop size distribution (DSD) moments. Unlike most schemes, however, it does not specify a DSD functional form.

This necessitates development of a moment-based polarimetric radar forward operator.

- The kth DSD moment (M_k) is

$$M_k \equiv \int_{D_{\min}}^{D_{\max}} N(D) D^k dD$$

D_{min}, D_{max}: minimum, maximum drop sizes
$N(D)dD$: number density of drops with diameters D to $D+dD$.

- Choice of prognostic moments will be partly based on the resultant ***uncertainty in our forward operator***.
- A given value of M_k can arise from an infinite number of DSDs. Our goal is to assess variability in the ***subset of realistic DSDs***.
- Here, we explore analytic DSDs, those produced by a state-of-the-art bin model, and DSDs from ARM disdrometer observations.

Analytic DSDs

- Use the gamma DSD: $N(D) = N_0 D^{\mu} \exp(-\Lambda D)$
- Compute self-consistent (M_k, M_j) pairs for k, j=[0, 20]. From each (M_k, M_j), two DSD parameters (N_0, Λ) are obtained for a wide range of μ similar to what has been observed.
- Compute Z_H, Z_{DR}, and K_{DP} from these DSDs using the T-matrix method (**Fig. 1**).

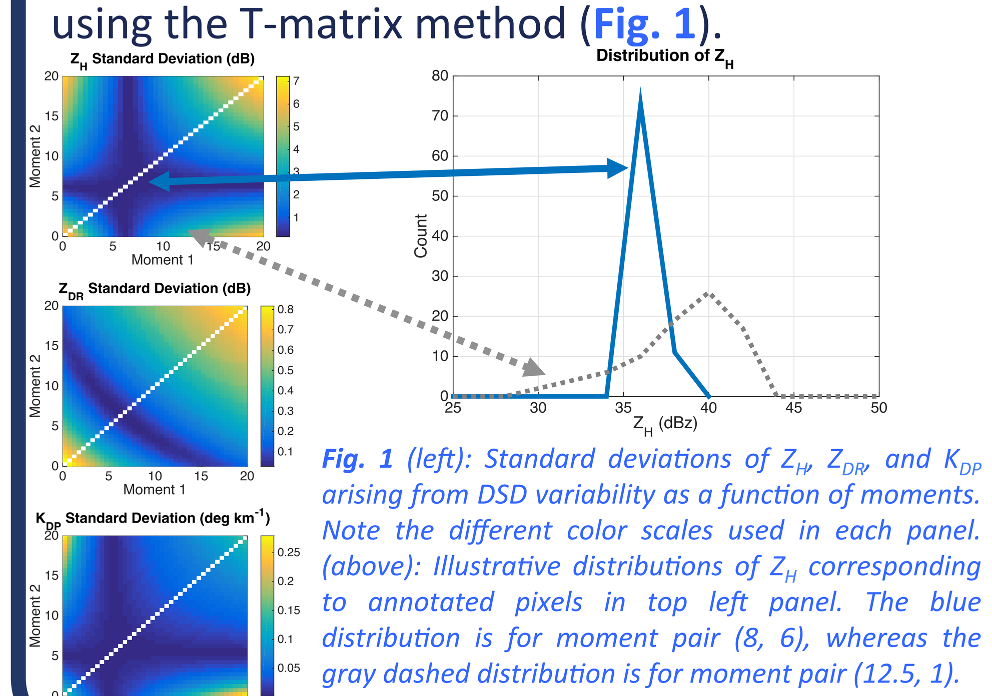

***Fig. 1** (left): Standard deviations of Z_H, Z_{DR}, and K_{DP} arising from DSD variability as a function of moments. Note the different color scales used in each panel. (above): Illustrative distributions of Z_H corresponding to annotated pixels in top left panel. The blue distribution is for moment pair (8, 6), whereas the gray dashed distribution is for moment pair (12.5, 1).*

- Define a combined variability parameter:

$$\Upsilon \equiv \frac{\sigma_{Z_H}}{\epsilon_{Z_H}} + \frac{\sigma_{Z_{DR}}}{\epsilon_{Z_{DR}}} + \frac{\sigma_{K_{DP}}}{\epsilon_{K_{DP}}}$$

ϵ : expected observational uncertainty
σ : standard deviation of radar variables for a given set of moments (M_k, M_j) arising from DSD variability

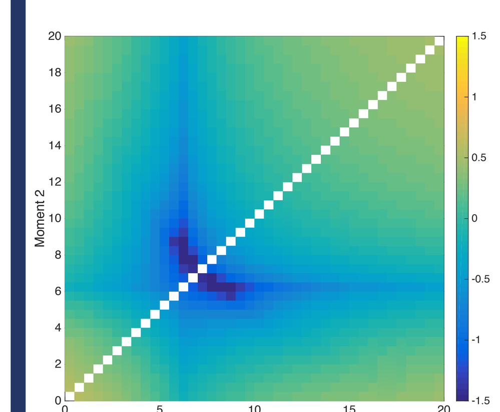

***Fig. 2**: Combined variability parameter Υ as a function of moment pair (shaded according to log scale). The initial DSD used to compute the moment pairs uses the μ-Λ relationship according to the Cao et al. (2008, JAMC). Low values indicate little variability in dual-pol variables for those moments.*

- **Fig. 2** suggests prognosing higher moments than traditional schemes in BOSS may improve the utility of polarimetric radar information as a constraint, limiting uncertainty in the forward operator.

Bin Model Simulation Data

- 1D bin microphysical model of Prat and Barros (2007, *JAMC*) used. Simulations run for 60 minutes (output Δt = 1 min) in a 3-km-tall domain (Δz = 10 m). Normalized gamma DSDs initialized at domain top with the following parameter ranges:

D_0: 0.2 mm to 4 mm
N_w: 100 to 80000 mm^{-1} m^{-3}
μ: -1 to 10

- Restrict to 0.01 mm hr^{-1} < R < 500 mm hr^{-1}, resulting in 10742 simulations.
- DSDs are taken at every output time and height, resulting approximately ***199 million DSDs***.

ARM Disdrometer Data

- PARSIVEL-2 and 2D video disdrometer data from ARM sites around the world are used.

- **PARSIVEL-2** (***15.5 million DSDs***)
  - SGP (2006-2016)
  - TWP (2006-2015)

- **2DVD** (***6.1 million DSDs***)
  - SGP (2011-2016)
  - ENA (2014-2016)
  - TWP (2011-2015)
  - GAN (DYNAMO-AMIE; 10/2011-2/2012)
  - TMP (BAECC; 2/2014-9/2014)

Combined Data: Results

- ***220.7 million "realistic" DSDs***; moments and dual-pol variables computed for each (**Fig. 3**).

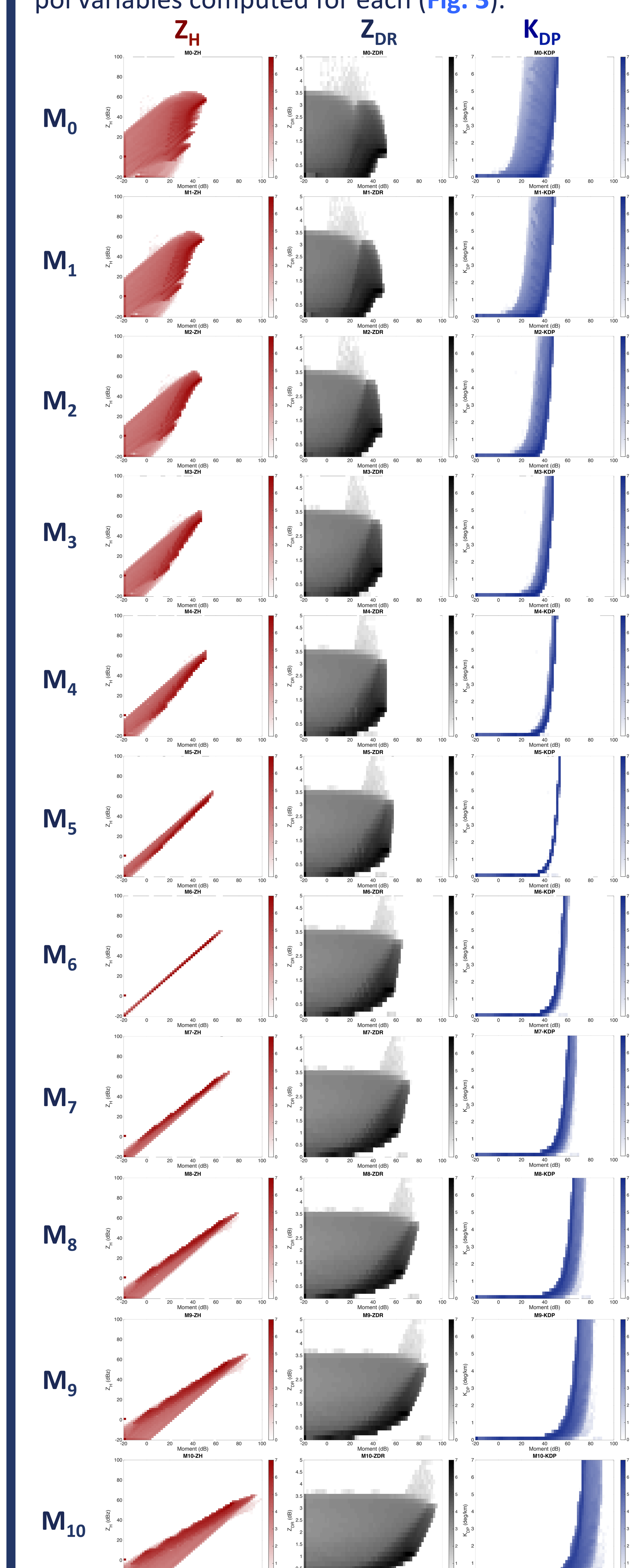

***Fig. 3**: 2D histograms showing the relationship between moments (rows) and the dual-polarization radar variables Z_H (red, left), Z_{DR} (black, middle), and K_{DP} (blue, right). Occurrence is shaded according to log scale. The combined dataset is used.*

- For the 2-moment BOSS, we desire the pair of predicted moments (M_k, M_j) that minimizes uncertainty in the forward operator (i.e., ***for which pair of moments do the dual-polarization radar variables provide the most information?***)
- Compute the distribution-weighted standard deviation for each radar variable X:

$$\xi \equiv \sum_{m}^{M} \sum_{n}^{N} \sigma_X \left[M_k^{(m)}, M_j^{(n)} \right] \times P \left[M_k^{(m)}, M_j^{(n)} \right]$$

where P is the joint pdf of M_k and M_j, which are discretized into M and N bins, respectively. Results for all (k, j) pairs considered are shown in **Fig. 4**.

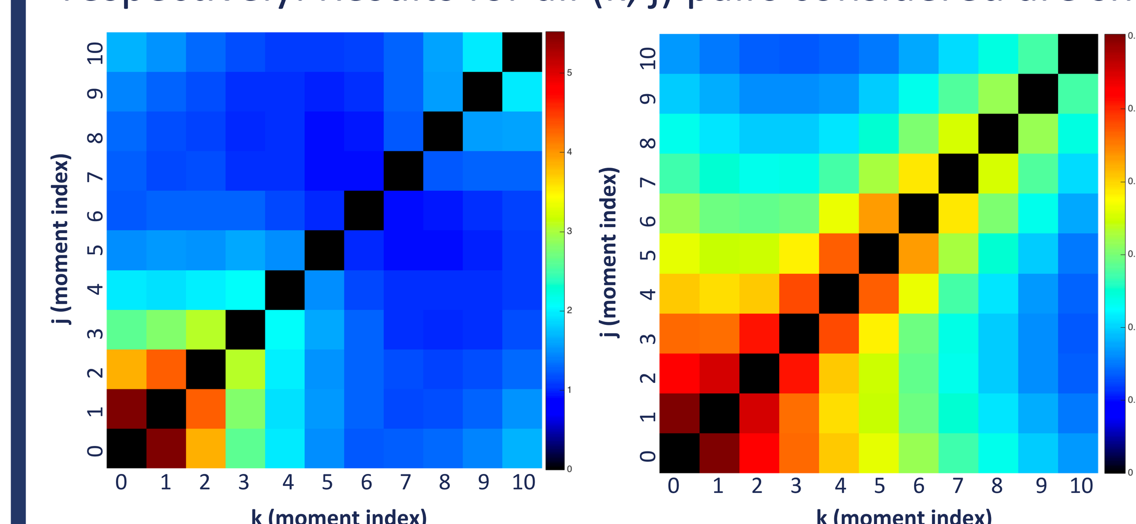

***Fig. 4**: ξ for (left) Z_H and (right) Z_{DR} as a function of moment indices k and j, shaded according to scale in dB. Combinations of moments (k, j) that have the least uncertainty in a given radar variable have lower values of bivariate ξ.*

- Formulate the forward operator for a number of different moment pairs (for 2-moment BOSS) or triads (for 3-moment BOSS). This will be in the form of a look-up table. **Fig. 5** shows an example of what this looks like for (M_6, M_8).

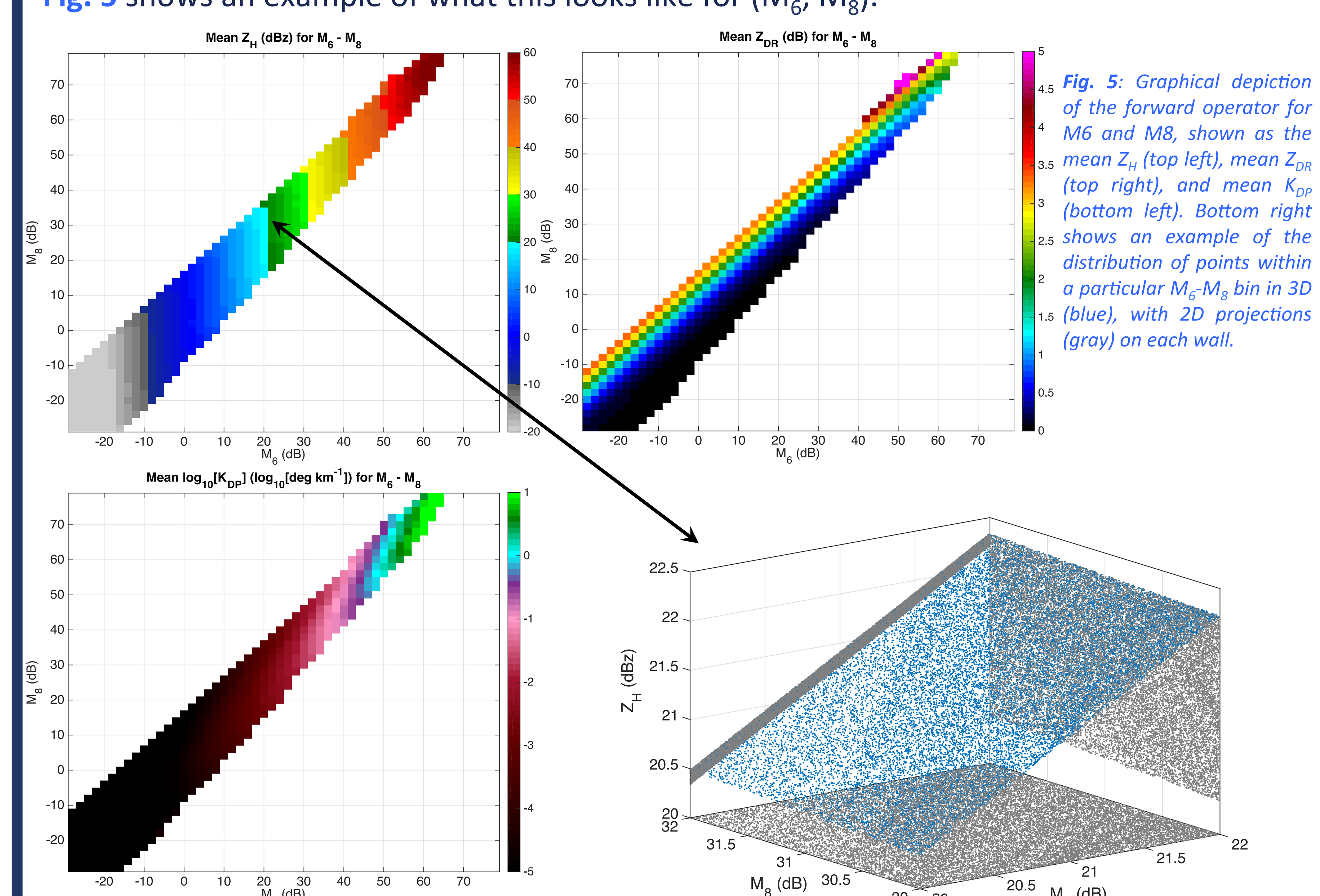

***Fig. 5**: Graphical depiction of the forward operator for M6 and M8, shown as the mean Z_H (top left), mean Z_{DR} (top right), and mean K_{DP} (bottom left). Bottom right shows an example of the distribution of points within a particular M_6-M_8 bin in 3D (blue), with 2D projections (gray) on each wall.*

- The forward operator must also account for the uncertainty within a given M_k-M_j bin. Thus, the look-up table will include not only the mean values of Z_H, Z_{DR}, and K_{DP} in each bin, but also the de-trended standard deviation of Z_H, Z_{DR}, and K_{DP} within a bin, as well as the distribution skewness, and covariances between the polarimetric radar variables.

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