Estimating core dynamics via the assimilation of magnetic field models into numerical dynamos

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Summary

We perform a series of numerical experiments with the Geomagnetic Ensemble Modeling System (**GEMS**, [1]) at NASA GSFC. GEMS is an Ensemble Kalman Filter (EnKF, [2]) based system which assimilates magnetic field models, defining the low-degree (large scale) features of the poloidal magnetic field of the outer core, into numerical dynamo models. Assimilation of field models into numerical dynamos results in estimates of core dynamics within the deep interior. We explore the capabilities and limitations of such a system, and highlight the importance of modern satellite-based magnetic observation systems such as SWARM.

Background

- GEMS assimilates Gauss coefficients of core-field models into an ensemble of numerical dynamo runs (see Figs. 1 & 2).

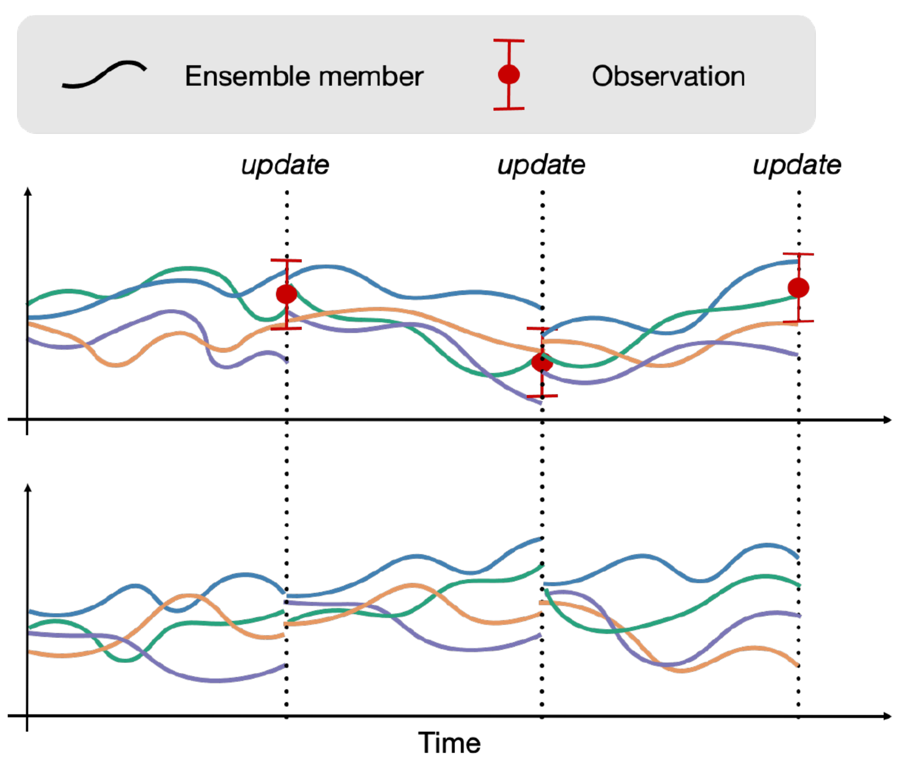

Figure 1: Illustration of the ensemble (EnKF) approach to assimilation used by GEMS. An ensemble of numerical dynamos (colored lines) is run forward through time. Periodically, "observations" (field model coefficients) are assimilated into the ensemble, with the ensemble statistics determining adjustments to both the "observed" magnetic field above the outer core, and the unobserved components of the dynamo (e.g., fluid flow).

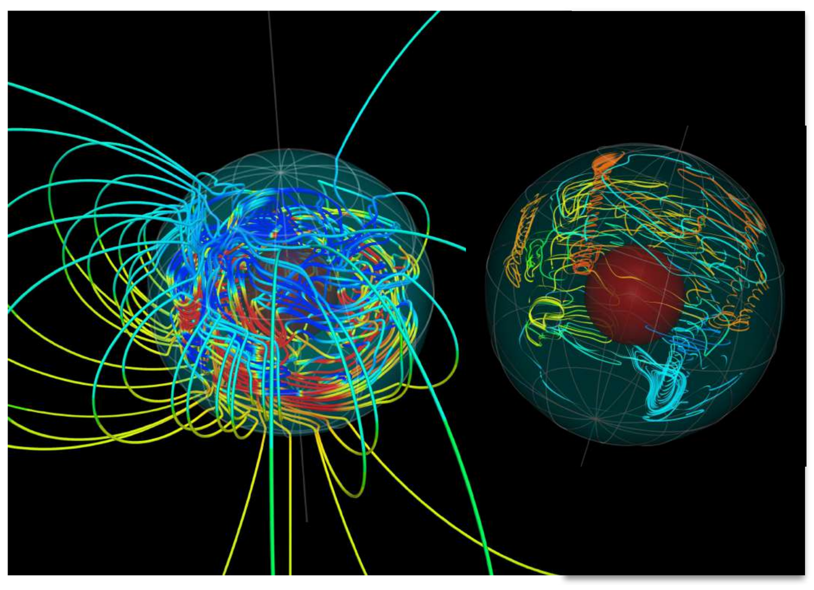

Figure 2: Snapshot of a typical dynamo simulation used in GEMS. The model consists of a magnetic field (single line shown on the left) coupled via induction and the Lorentz force to an electrically-conducting fluid (streamlines of fluid flow shown on right).

- It is known that, while capable of generating "Earth-like" magnetic fields, current numerical dynamo simulations are run in parameter regimes that differ from those of the Earth [3].
- **Model bias from incorrect dynamo parameters may inhibit the ability of GEMS to estimate the core state** because the incorrect dynamics and ensemble statistics (see Fig. 1) during assimilation.

Numerical experiments

- **We perform Observing System Simulation Experiments (OSSEs)** where a free run (no assimilation) of a dynamo model is recorded as the "ground truth", which GEMS estimates through assimilation of noisy Gauss coefficients defining the "observable" magnetic field.
- To simulate model bias, the dynamo used in generating the synthetic data uses parameters which differ from those of the assimilation model (see table 1 and e.g., [4]).

	R_O, E	R_{th}	q_k
Synthetic data model	6.25 x 10^{-7}	1811	1
GEMS assimilation model	2.5 x 10^{-6}	905	1

Table 1: Values of the Rossby (R_O), Ekman (E), Rayleigh (R_{th}) and modified Prandtl number (q_k) use in the generation of synthetic data for OSSEs (top row) and the assimilation system (bottom row).

- For "observation" noise we use the uncertainties of Kalmag [5] in 2018.0 and **the time between assimilations is approximately one year** (according to the typical timescales of the $\ell \leq 3$ "observable" magnetic field of the synthetic data model).

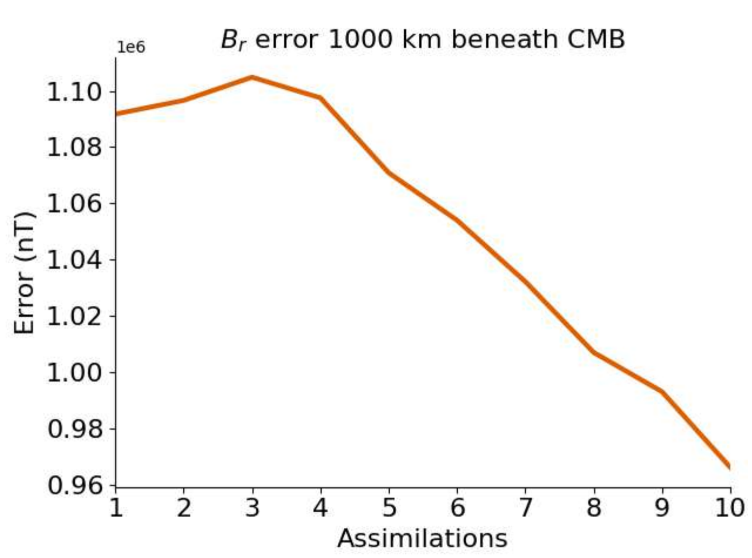

Figure 3: Error in radial magnetic field estimate 1000 km below the core-mantle boundary (CMB) as a function of assimilation (assimilating $\ell \leq 13$) using an ensemble of $N_e = 512$. Over time, assimilation can begin to "nudge" the deep interior field towards the true state.

Results

- We run two OSSEs with identical initial ensembles ($N_e = 512$), shrinkage localization, and radial localization [6], but assimilating field models either through degree 8 or degree 13 (see Figs. 4, 5)

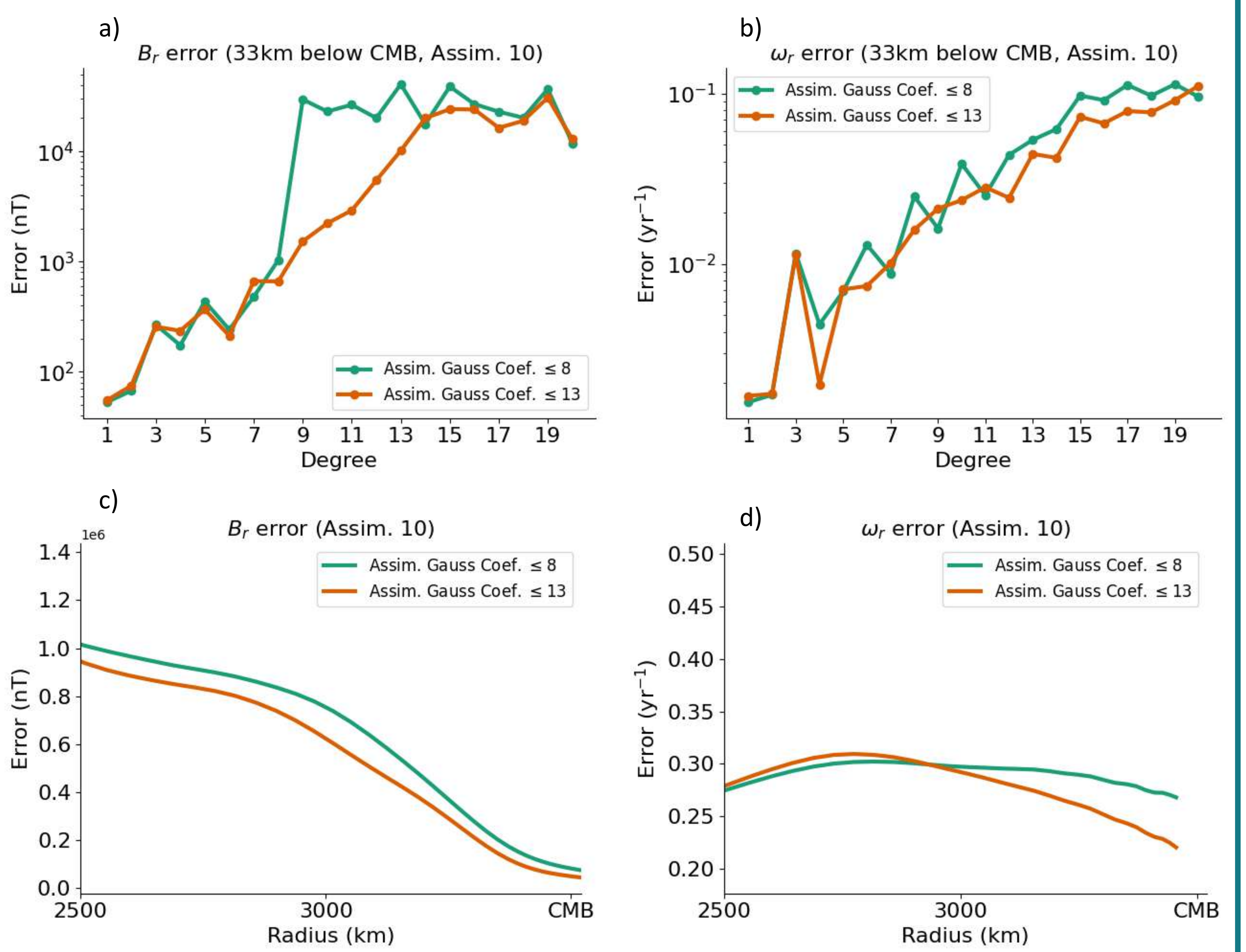

Figure 4: Error in OSSEs assimilating "observable" magnetic field through degree 8 (green) and degree 13 (orange) on the tenth assimilation. **Assimilating higher degree Gauss coefficients** $(8 < \ell \leq 13)$ **reduces errors, even among larger length-scale features,** (i.e., $\ell \leq 8$). (a) Intensity error, by spherical harmonic (SH) degree, in the radial magnetic field B_r 33km below the CMB. (b) Error, by SH degree, in radial vorticity ω_r of the horizontal flow 33km below the CMB. (c) Intensity error in B_r as a function of depth. (d) Error in ω_r as a function of depth.

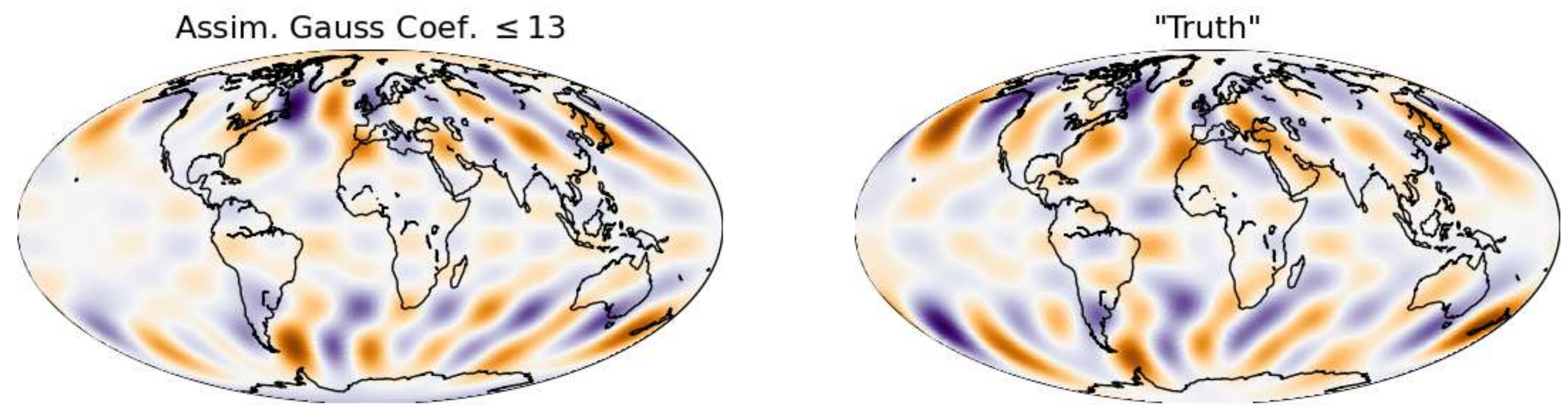

Figure 5: Radial vorticity ω_r (orange is counterclockwise flow, purple is clockwise) 33km below the CMB , after the tenth assimilation of Gauss coefficients $\ell \leq 13$ (left), compared to the true state (right). Distributions are normalized by the largest value and truncated at degree 8. **After ten assimilations, GEMS has begun to recover several large-scale features of the flow.** However, smaller-scale (higher degree) features (not shown) do not show a notable a reduction in error.

Concluding remarks

- Similar to [4], we find that higher-degree information on the magnetic field from satellite missions such as SWARM, are critical to inferring the state of the core.
- We also find (similar to [4]), little evidence that the assimilation, over the time period considered, leads to improved estimates of the toroidal magnetic field, the poloidal fluid flow (not shown) or smaller-scale features of the horizontal flow.
- Errors are still being reduced at the time of the tenth assimilation (shown above) and therfore, sustained, satellite-based observations, enabling the continuation of modern, high-degree field models of the core, are essential to improving estimates of core dynamics.

References

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