

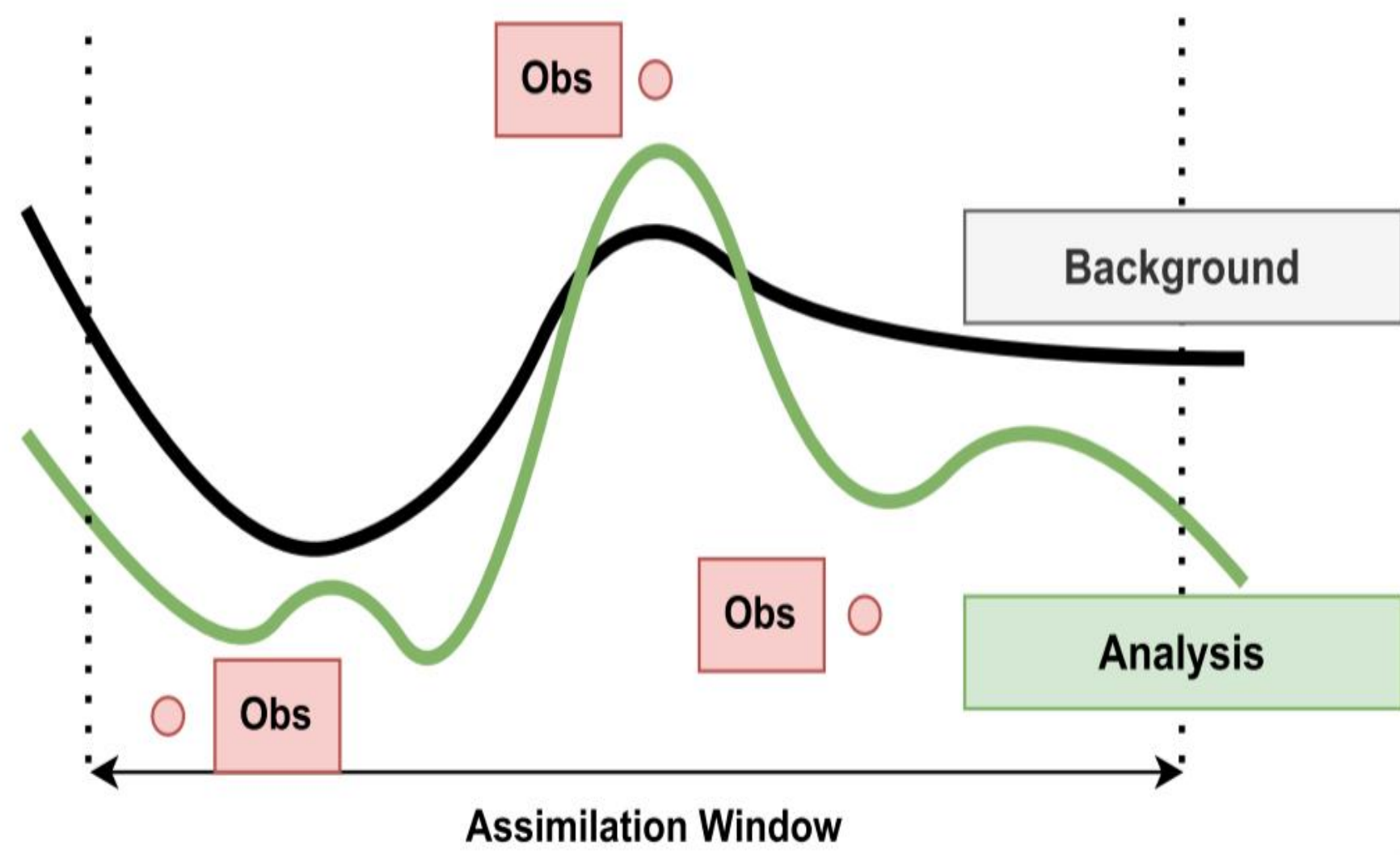
LoPhyDA: Low-Rank Tensor and Physics Gradient Guided Diffusion for Atmospheric Data Assimilation

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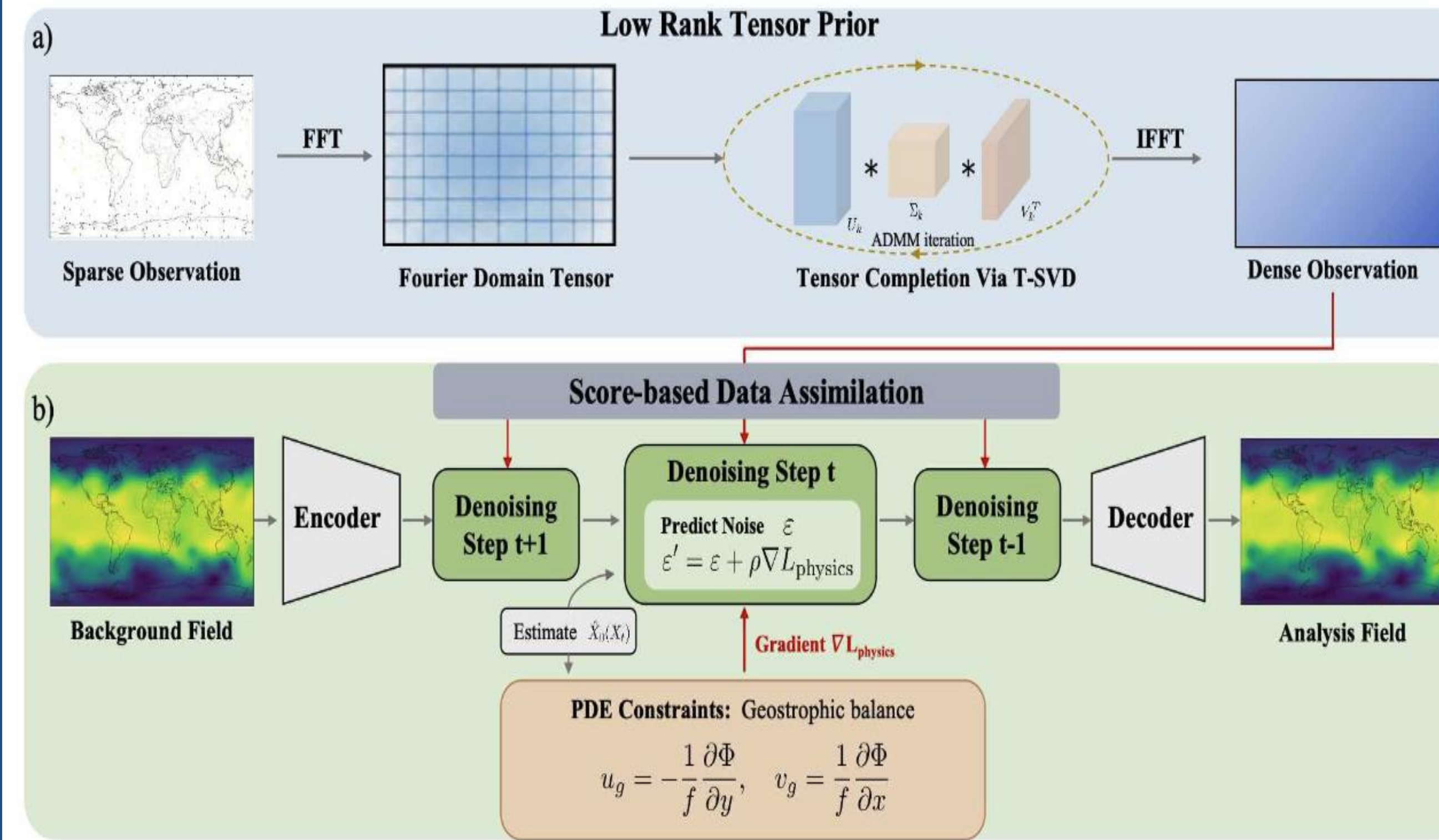
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1. Introduction



- We propose **LoPhyDA**, a *diffusion assimilation* framework that jointly leverages global priors and local physical constraints to **reduce state-estimation uncertainty under sparse observations**.
- A **low-rank tensor-based *observation reconstruction*** method is proposed to recover dense fields from sparse and discontinuous observations, enhancing global structural consistency.
- A **physical gradient-guided** inference method is introduced to *enforce local physical consistency* during denoising.

2. Method: LoPhyDA



3. Main Results

➤ Simulated observations

Model	MAE	MSE	WRMSE						
			z500	t850	t2m	u10	v10	u500	v500
Background	0.1496	0.0565	98.3628	1.9722	5.6729	1.2765	1.1882	2.1649	2.3277
SDA	0.1385	0.0401	78.7688	1.5014	5.3589	0.9998	0.8909	2.0228	1.4821
DiffDA	0.1368	0.0375	75.5332	1.3728	4.8517	0.7659	0.7461	1.7698	1.3842
AlignDA	0.1267	0.0353	68.6661	1.3076	4.6337	0.7935	0.7245	1.6064	1.1813
PhyDA	0.1225	0.0347	71.6741	1.1033	4.7928	0.8062	0.7196	1.2435	1.4766
LoPhyDA	0.1183 (↓3.55%)	0.0336 (↓3.27%)	58.8376	1.1217	4.4293	0.7178	0.6811	1.4919	1.0229

➤ Real observations

Model	MAE	MSE	WRMSE						
			z500	t850	t2m	u10	v10	u500	v500
Background	0.1440	0.0571	99.8706	1.9692	5.8989	1.2588	1.2406	2.0761	2.4066
DiffDA	0.1275	0.0428	78.8742	1.4428	4.7613	0.8935	0.7321	1.7698	1.4950
AlignDA	0.1241	0.0413	73.2120	1.3709	4.5811	0.8164	0.7069	1.6964	1.3748
LoPhyDA	0.1206 (↓2.82%)	0.0385 (↓6.78%)	65.4817	1.0376	4.3791	0.6874	0.7005	1.4075	1.2639

4. Ablation Study

Model	MAE	MSE	WRMSE						
			z500	t850	t2m	u10	v10	u500	v500
LDA	0.1386	0.0415	82.3469	1.4726	5.3712	0.9765	0.8738	1.9743	1.5238
LDA-Phy	0.1319	0.0388	75.4131	1.4964	5.2932	0.9236	0.8225	1.7681	1.3059
LDA-LoR	0.1235	0.0365	65.3315	1.2312	4.6135	0.7203	0.7367	1.6645	1.2158
LoPhyDA	0.1183	0.0336	58.8376	1.1217	4.4293	0.7178	0.6811	1.4919	1.0229

Achieving superior performance via low-rank tensor-based observation reconstruction

5. Cyclic assimilation and forecasting

