Thank you for the detailed review and suggestions on ways we can improve the manuscript. Your feedback is very much appreciated! The following text includes a point by point response to each comment.

Review 1: Further explanation of the physical meaning of regularization: The spatial and temporal continuity regularization terms enhance smoothness in downscaling fields. However, further explanation of their physical relevance would increase interpredictability, such as how these constraints reflect realistic atmospheric system evolution characteristics.

Response 1: Thank you for your suggestion to elaborate on the physical relevance of the spatial and temporal continuity regularization terms. We agree that additional explanation would enhance the interpretability of these constraints in the context of atmospheric system evolution. The spatial and temporal continuity regularization terms are designed to reflect the inherent smoothness and gradual progression commonly observed in atmospheric processes. Atmospheric fields typically exhibit continuity across both spatial and temporal dimensions due to physical constraints like mass conservation, energy balance, and fluid dynamics, which govern the evolution of these systems (Lorenz, 1969; Holton and Hakim, 2012). For instance, atmospheric variables such as temperature and humidity tend to vary gradually over short distances and time intervals, as abrupt changes are physically unrealistic under normal conditions. Spatial continuity regularization enforces a smooth gradient across neighboring grid points, simulating how atmospheric properties tend to vary continuously across regions. This aligns with principles of geophysical fluid dynamics, which suggest that atmospheric variables are influenced by local surroundings, leading to correlated values across neighboring points (Charney, 1948; Gill, 1982). Temporal continuity regularization, on the other hand, helps ensure that changes in the downscaled fields remain consistent over consecutive time steps. This reflects the physical principle that, barring extreme events, atmospheric properties do not undergo sudden, large fluctuations within short time intervals. Gradual transitions are typical due to the inertia in atmospheric systems and the continuous nature of energy and momentum transfer across time (Emanuel, 1994). Temporal coherence is especially relevant in meteorological applications where the predictability of evolution patterns—such as the movement of weather fronts or pressure systems—relies on smooth temporal transitions. Incorporating these regularization terms therefore makes the downscaling model more physically plausible by emulating the inherent continuity of atmospheric fields.

Review 2: Evaluation of Model Complexity and Computational Efficiency: Although this approach outperforms other unsupervised methods in restoration rate, the computational cost’s impact on practical applications remains undiscussed. Evaluating the model’s computational efficiency, especially in large-scale meteorological datasets or real-time applications, would provide valuable insights.

Response 2: Thank you for raising this important point. We agree that discussing the model’s computational efficiency is valuable, particularly given the demands of large-scale meteorological datasets and potential real-time applications. We have added an evaluation of the model's computational complexity and efficiency in the revised manuscript. In this evaluation, we examine the model's runtime and resource requirements, including memory usage and processing time per sample, relative to other unsupervised methods. We also discuss the feasibility of applying TemDeep in operational settings and highlight the efficiency gains achieved through architectural optimizations, such as the use of an encoder-decoder structure with residual blocks and efficient regularization terms.

Review 3: Add more discussion on comparison with traditional down-scaling methods: to illustrate the advantages of TemDeep comparing to one or more physics-based numerical models, explain why this approach achieves superior performance in restoration rate and consistency under unsupervised conditions could offer deeper insights.

Response 3: Thank you for this suggestion. We agree that a detailed comparison with traditional physics-based downscaling methods adds value by highlighting the advantages of TemDeep in restoration rate and consistency. In the revised manuscript, we have expanded our discussion to compare TemDeep with traditional downscaling approaches, such as dynamical downscaling models like the Weather Research and Forecasting (WRF) model (Skamarock et al., 2008) and statistical methods based on regression or autocorrelation techniques (Fowler et al., 2007). Traditional methods rely heavily on precise physical parameterizations and initial conditions to simulate atmospheric dynamics, which can be computationally intensive and sensitive to input uncertainties, often limiting their scalability for high-resolution, long-term applications (Lorenz, 1969; Maraun et al., 2010). TemDeep, in contrast, leverages a self-supervised deep learning framework that capitalizes on temporal coherence within atmospheric data, enabling it to generalize well without requiring high-resolution ground truth data for training.

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