

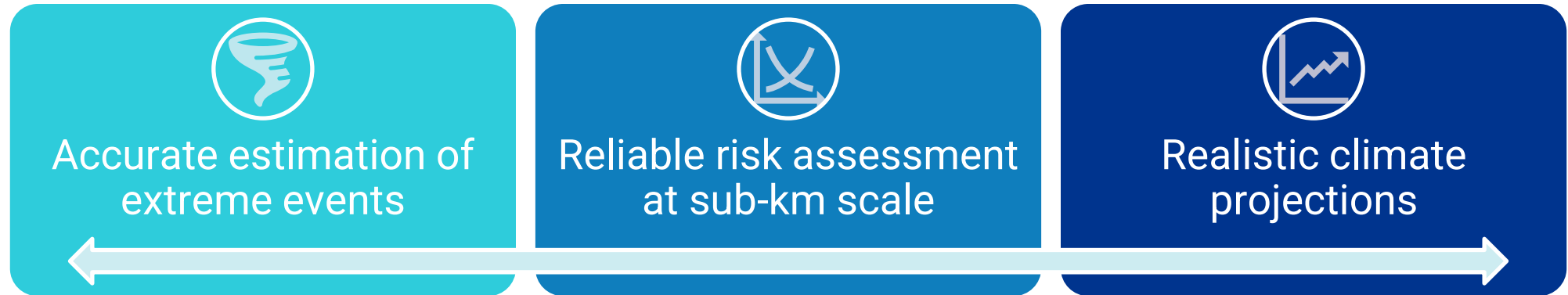


# TAUDiff: Improving Statistical Downscaling for Extreme Weather Events Using Generative Diffusion Models

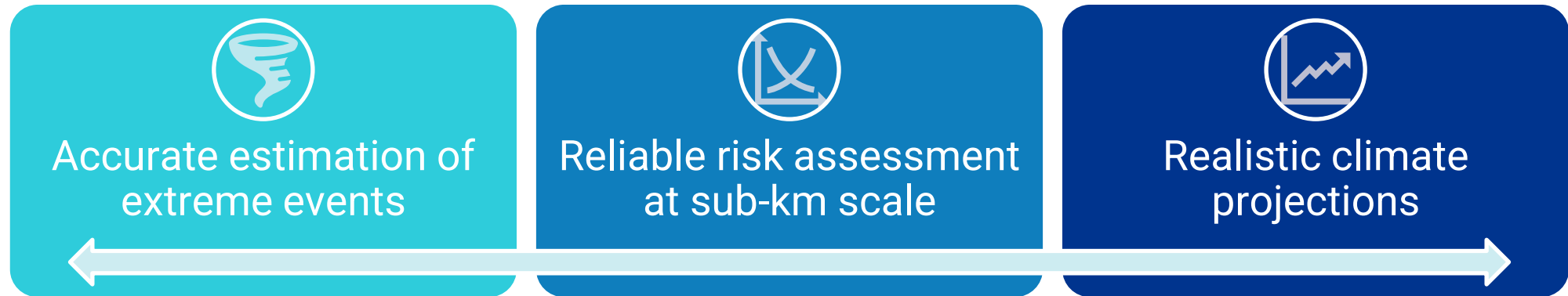
**Rahul Sundar**  
**Nishant Parashar**  
**Antoine Blanchard**  
**Boyko Dodov**

*Tackling Climate Change with  
Machine Learning @ NeurIPS 2024*

# Physically Consistent Statistical Downscaling of Climate Variables is Crucial for Extreme Weather Projections



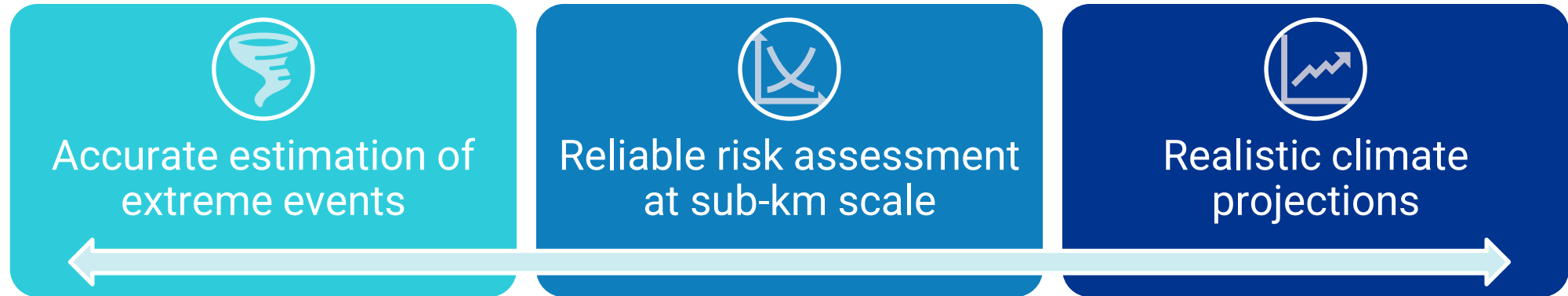
# Physically Consistent Statistical Downscaling of Climate Variables is Crucial for Extreme Weather Projections



## Deterministic regression-based downscaling

- ▲ Computationally efficient during inference
- ▼ Misses fine-scale features (spectral bias)
- ▼ Does not capture extremes accurately

# Physically Consistent Statistical Downscaling of Climate Variables is Crucial for Extreme Weather Projections



## Deterministic regression-based downscaling

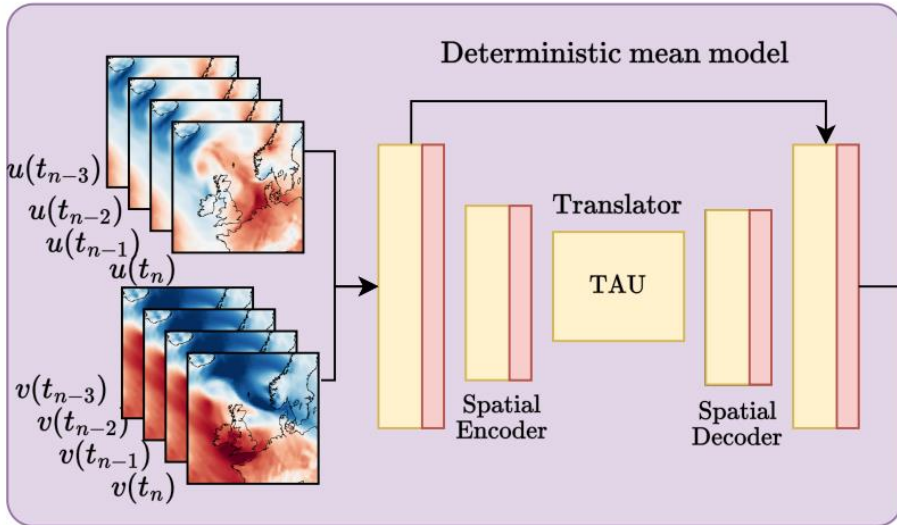
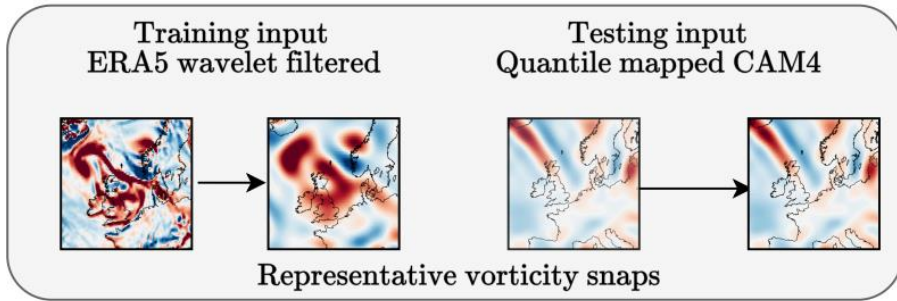
- ▲ Computationally efficient during inference
- ▼ Misses fine-scale features (spectral bias)
- ▼ Does not capture extremes accurately

## Generative diffusion models

- ▲ Can generate stochastic fine scale features
- ▼ Are computationally expensive at inference when trained end-to-end

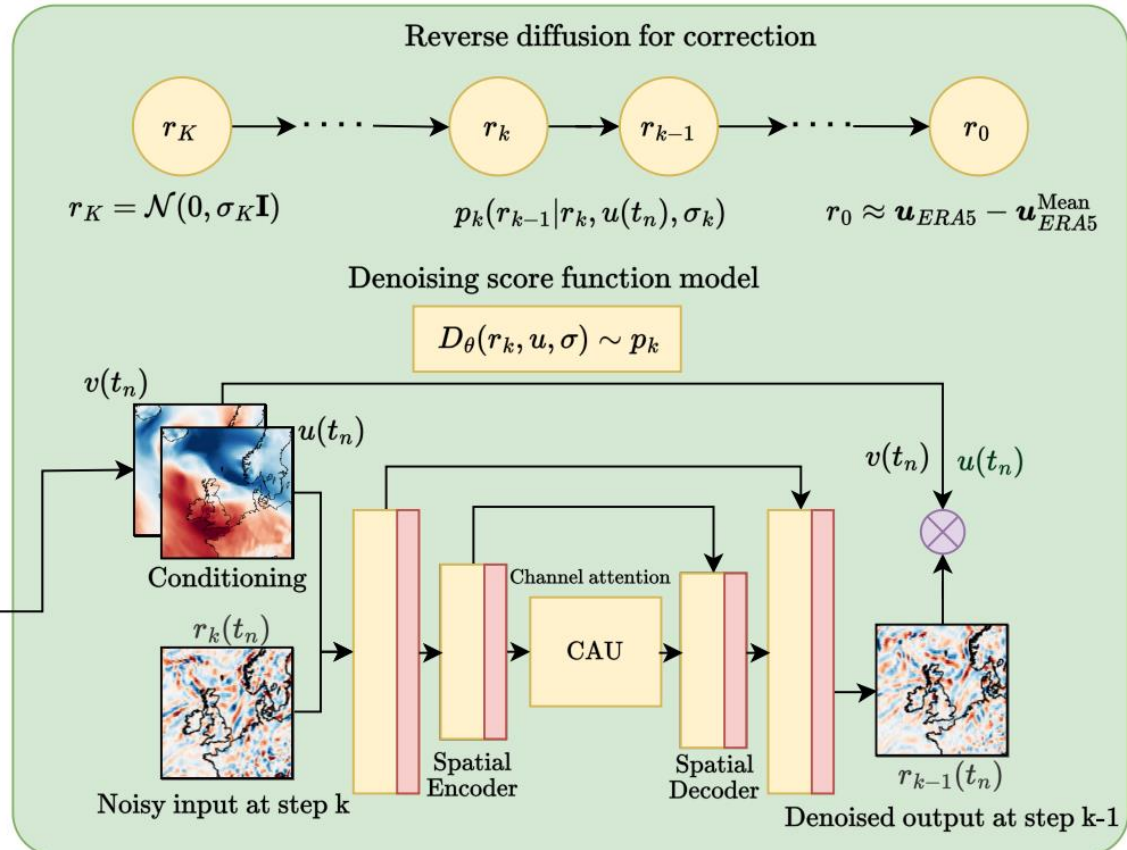
# Temporal Attention Unit Enhanced Diffusion Model (TAUDiff)

Temporal history conditioned mean field model + correction-diffusion architecture



Mean field model (deterministic large-scale features)

TAU: Temporal Attention Unit



Correction-diffusion model (stochastic fine-scale features)

CAU: Channel Attention Unit

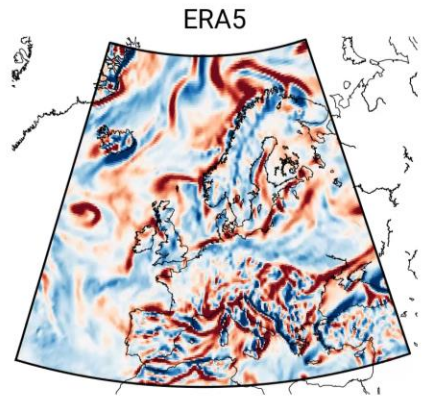
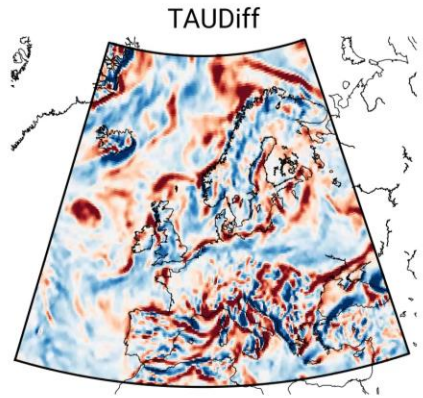
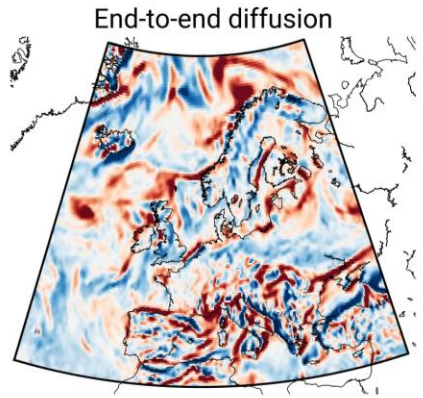
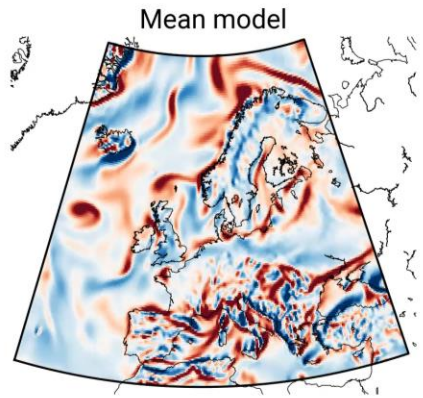
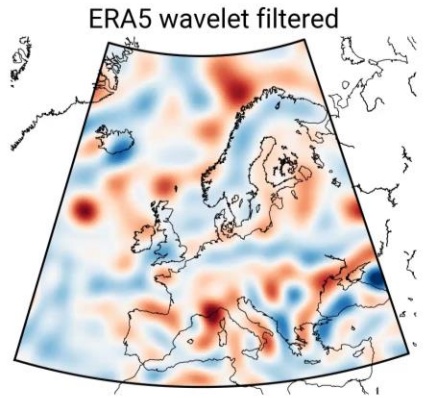
# TAUDiff Validation

## Wavelet filtered ERA5 data downscaling



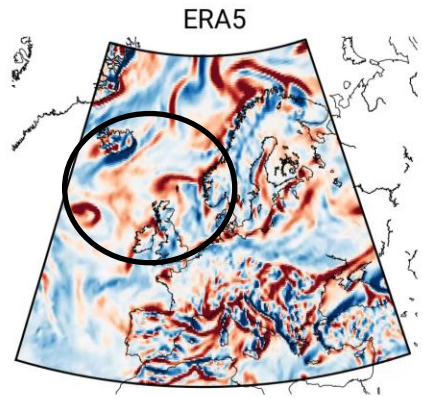
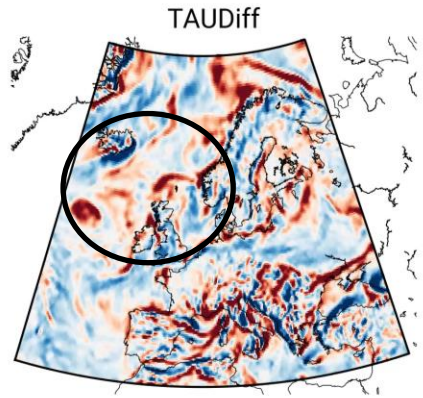
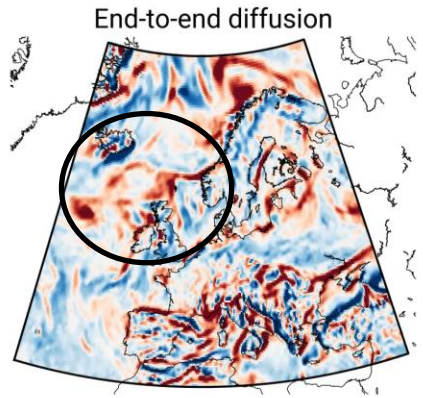
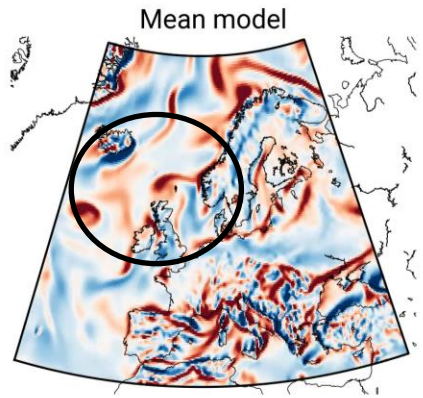
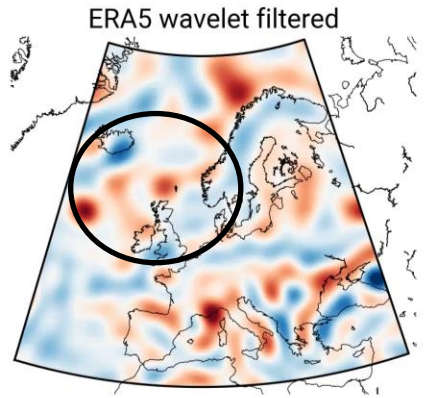
# TAUDiff Validation

## Wavelet filtered ERA5 data downscaling



# TAUDiff Validation

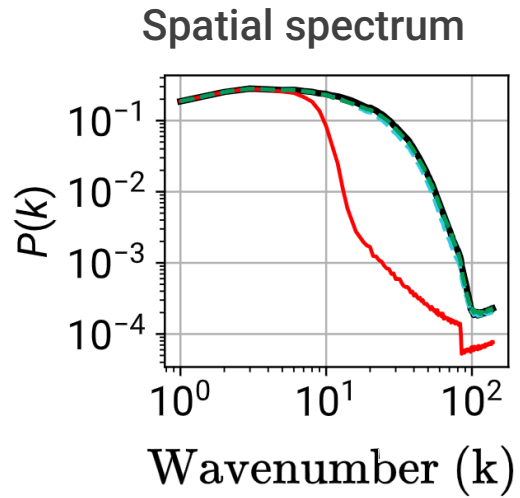
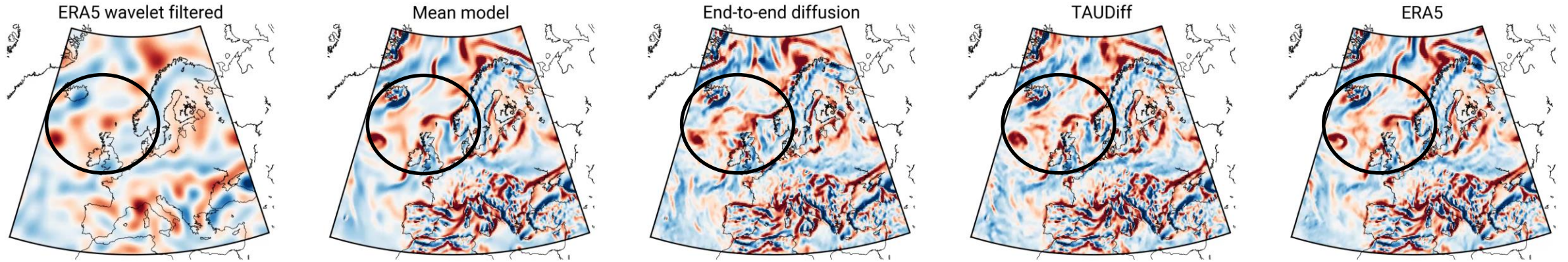
## Wavelet filtered ERA5 data downscaling





# TAUDiff Validation

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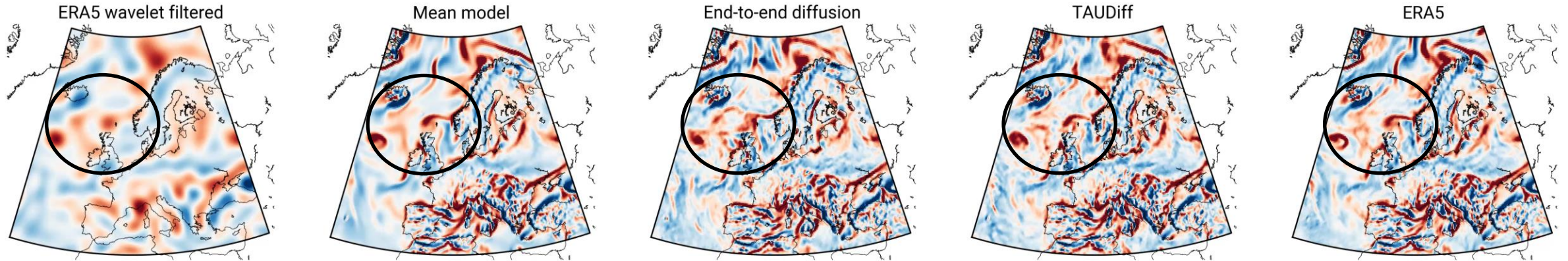


— ERA5    - - - End-to-End diffusion  
— ERA5 - Wavelet Filtered    - - - TAUDiff

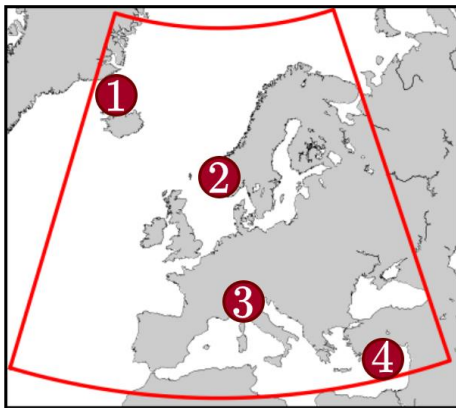
- Fronts and waves dynamically consistent
- Full ERA5 spatiotemporal spectral recovery obtained

# TAUDiff Validation

## Wavelet filtered ERA5 data downscaling



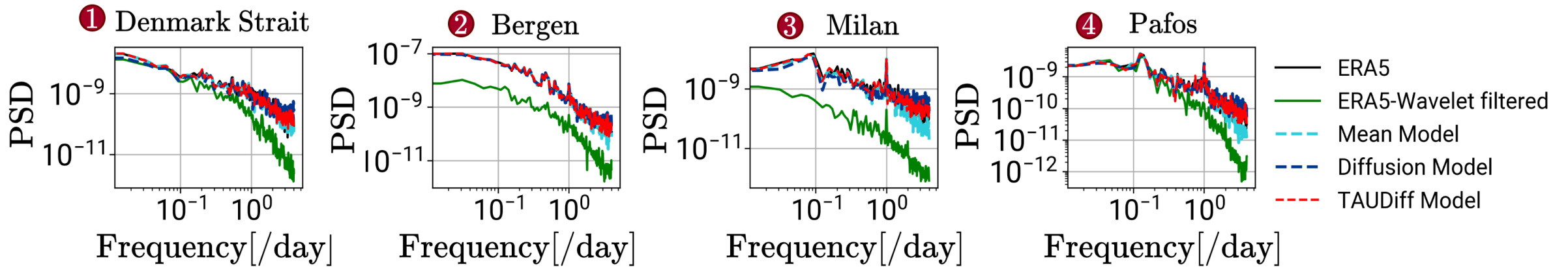
European domain and locations considered



- Fronts and waves dynamically consistent
- Full ERA5 spatiotemporal spectral recovery obtained
- Pointwise statistics and correlations consistent with reanalysis

# TAUDiff Validation

## Wavelet filtered ERA5 data downscaling



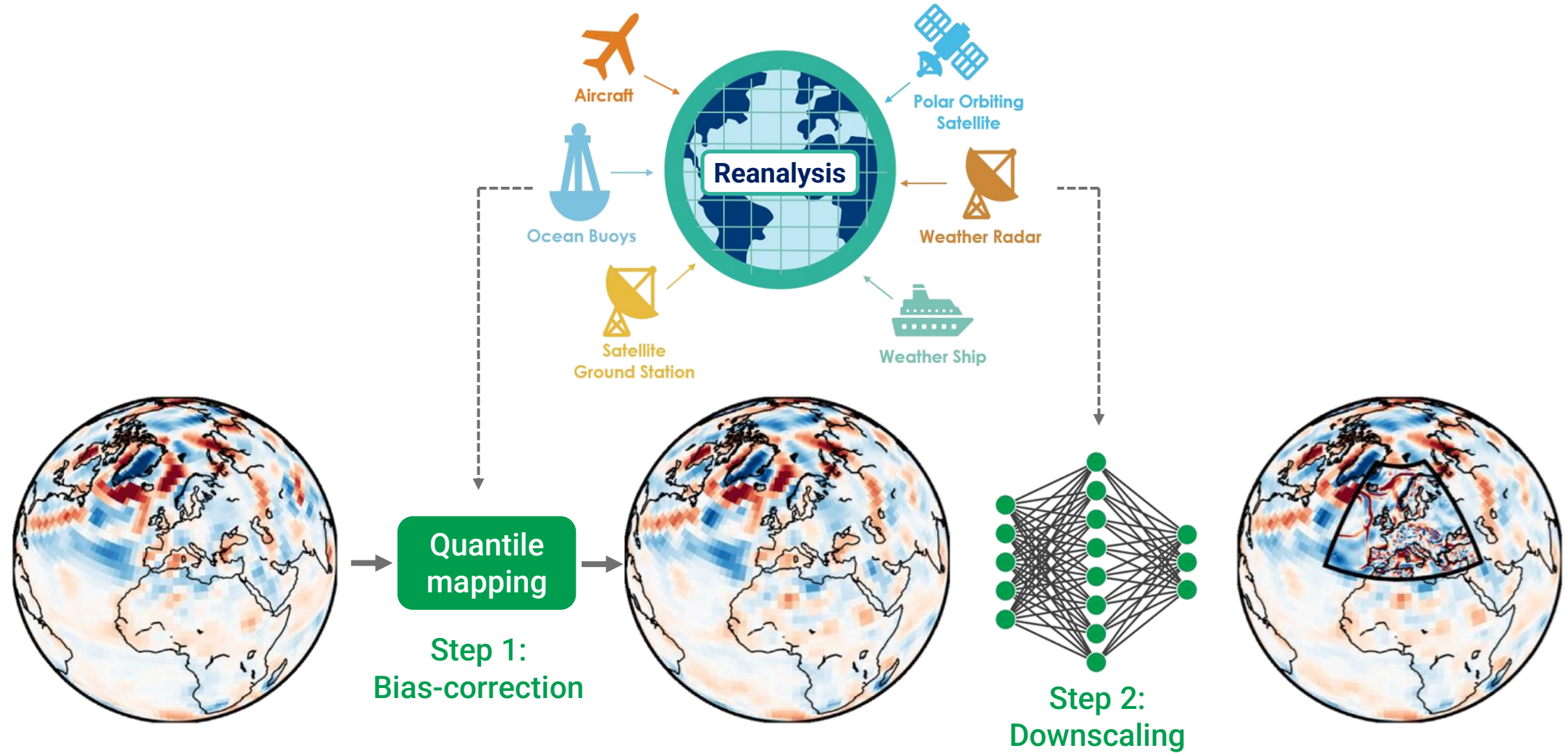
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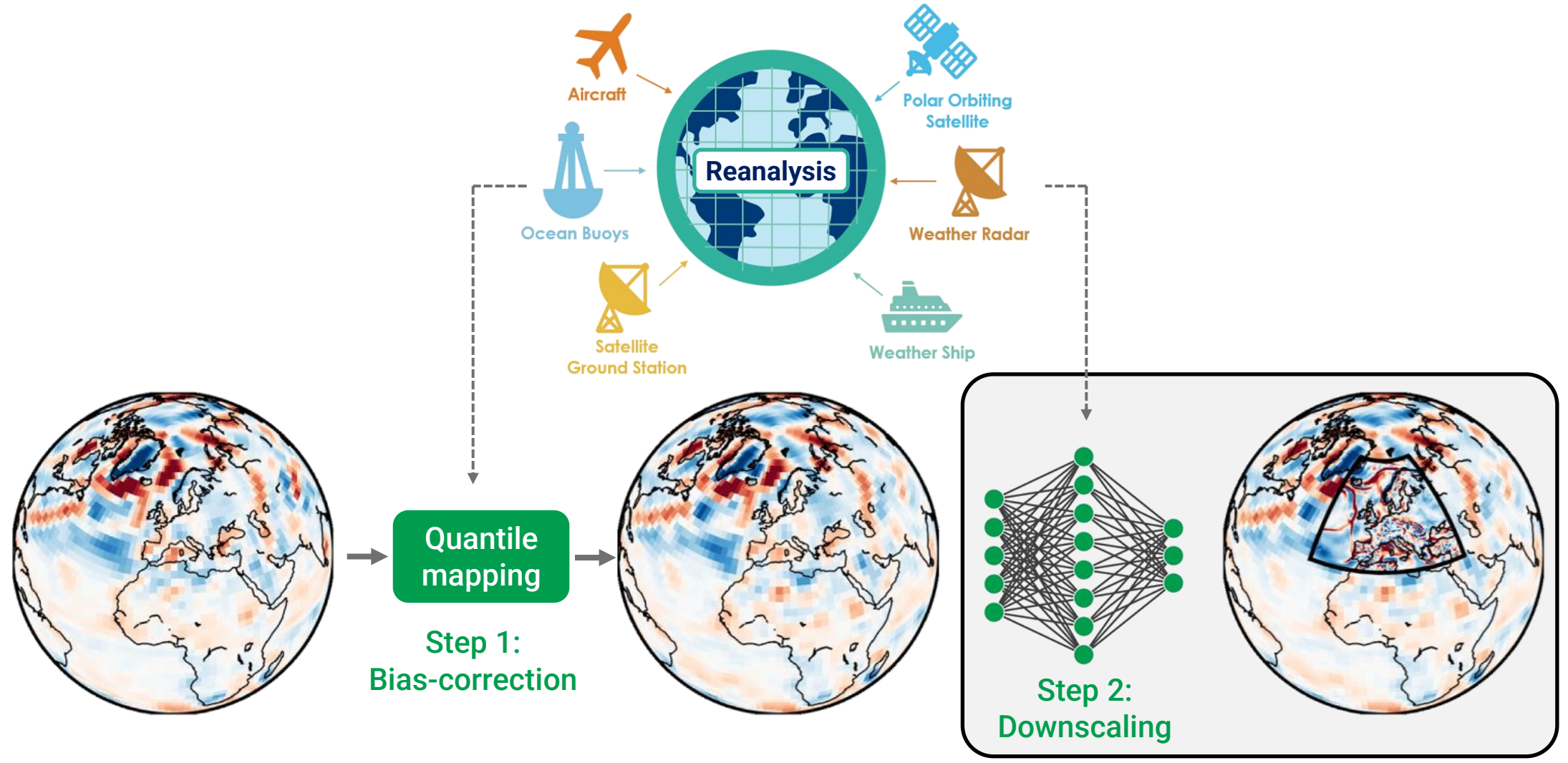
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# ML Pipeline for Downscaling Physics based GCM Simulations

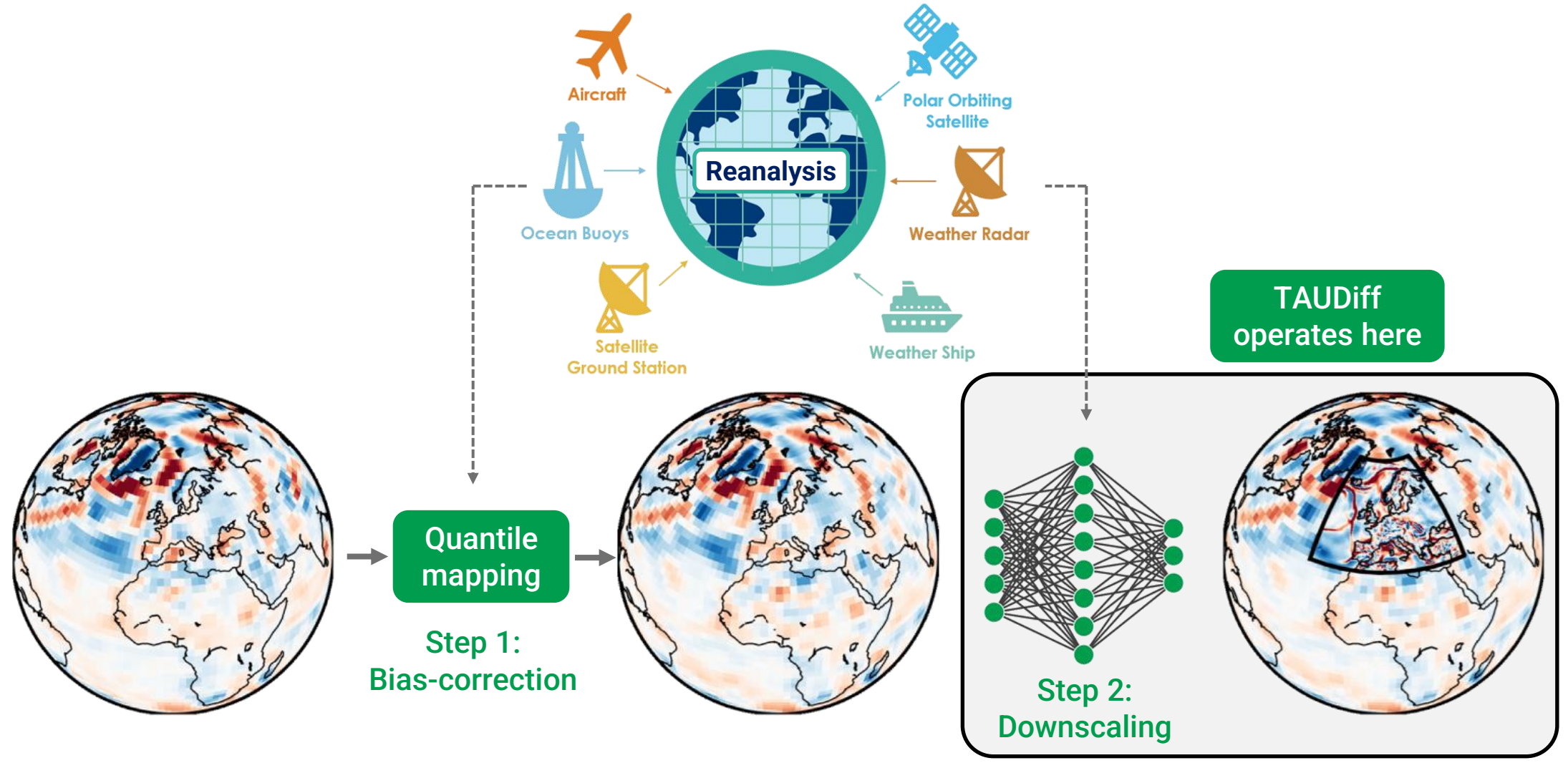


# ML Pipeline for Downscaling Physics based GCM Simulations





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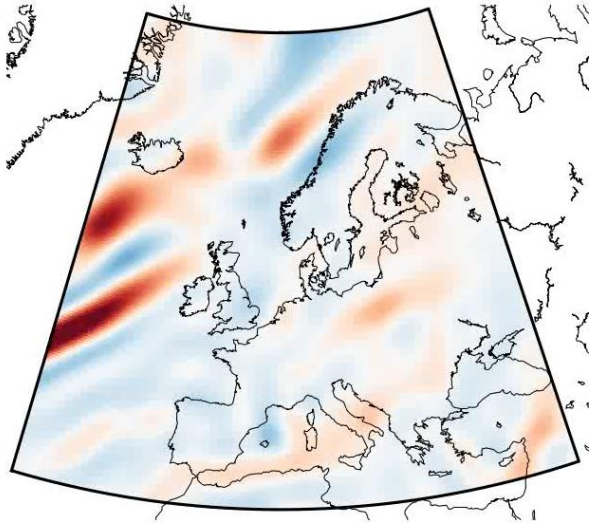
# TAUDiff Testing

## GCM data downscaling

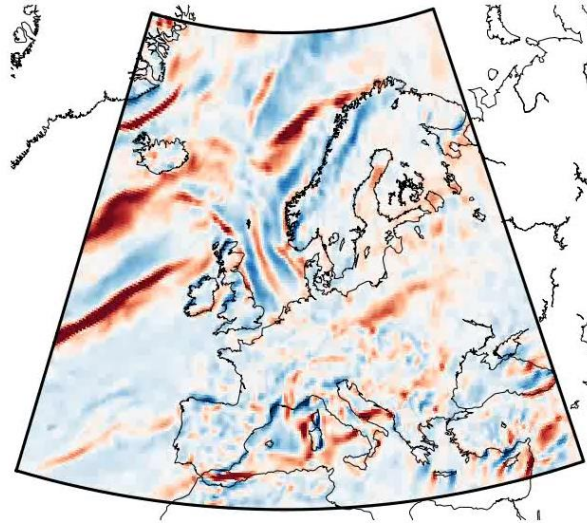
# TAUDiff Testing

## GCM data downscaling

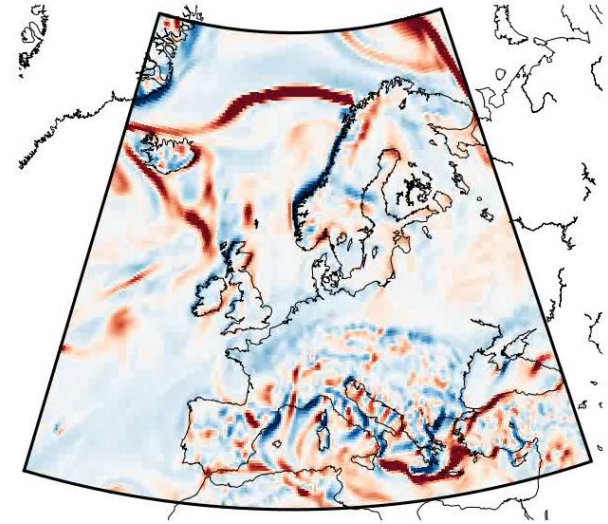
Raw CAM4



Bias-corrected and downscaled  
CAM4 (TAUDiff)



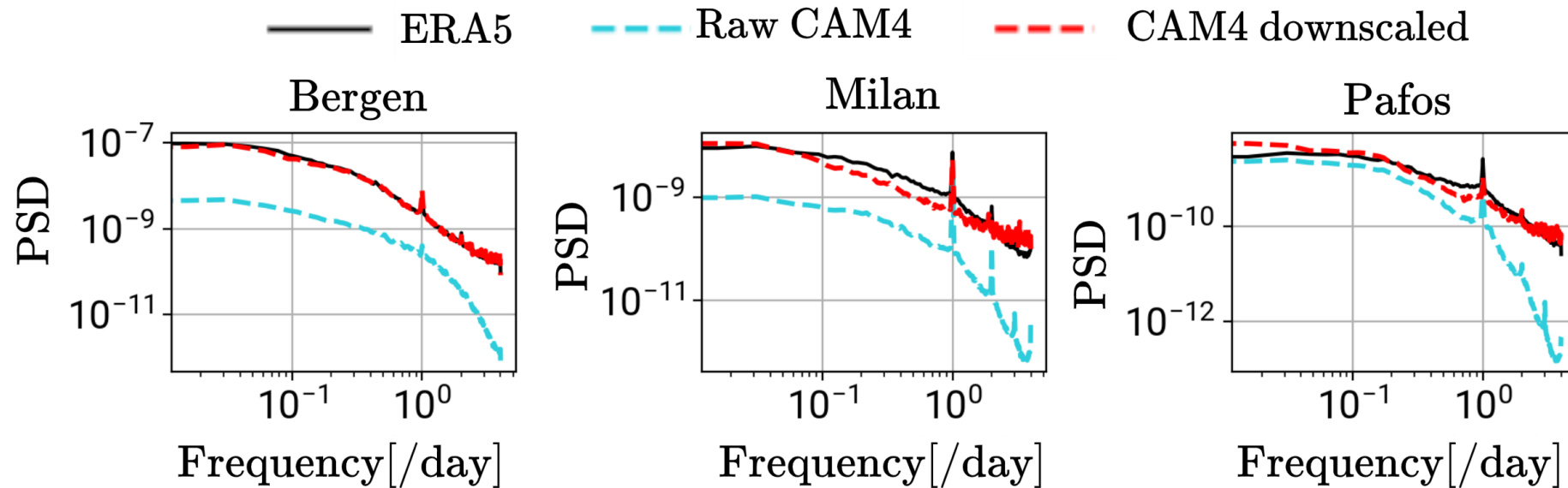
ERA5 reference



- CAM4 chosen as the GCM (~100 km resolution)
- Bias-corrected CAM4 downsampled to ~25 km with full spectral recovery over European region

# TAUDiff Testing

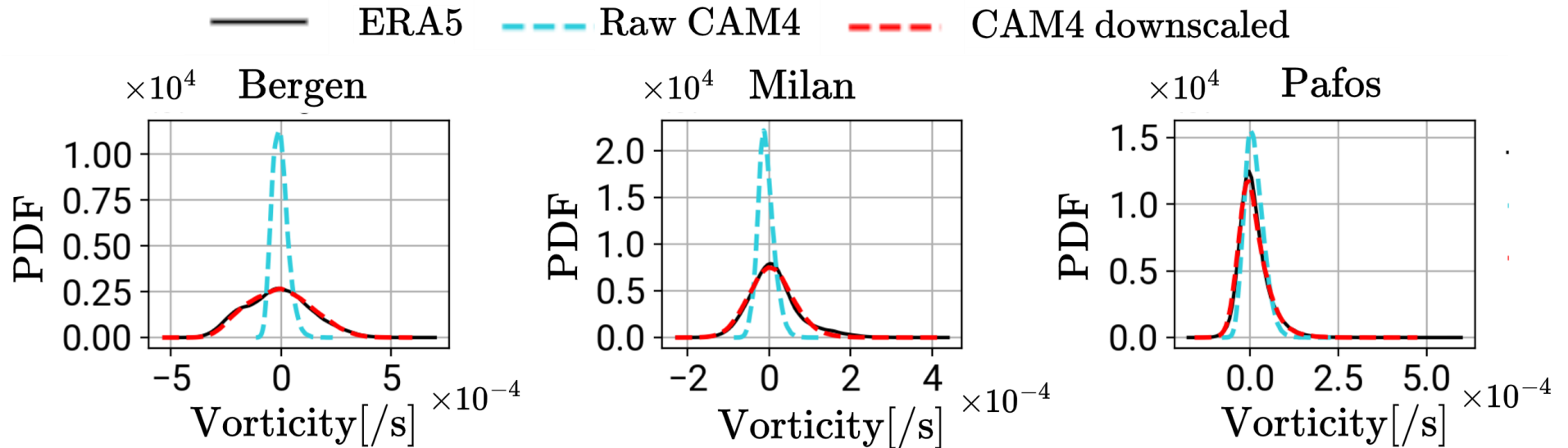
## GCM data downscaling



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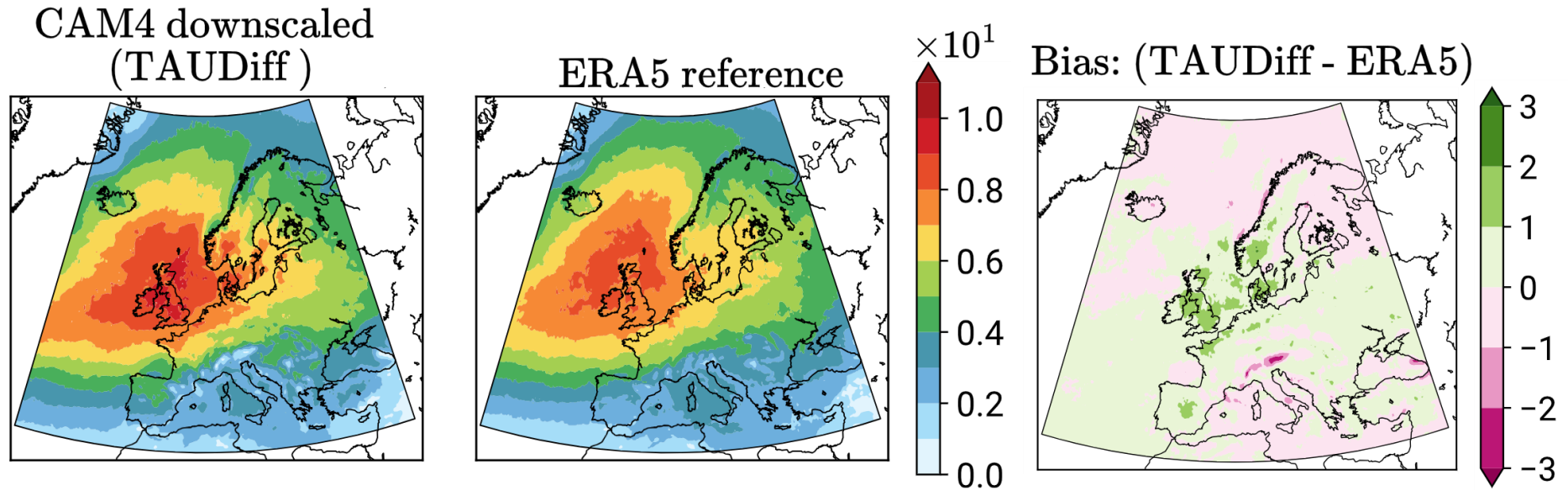


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# Conclusions

**Video-prediction inspired model**  
*for dynamically consistent downscaling of climate variables*

**Remarkable performance on extreme events**  
*with full spectral recovery and pointwise statistics*

**Much smaller (100x) correction-diffusion model**  
*versus  $O(100M)$  models often used in literature*

**Faster inference (2.5x), lower memory and carbon footprint**  
*as compared to an end-to-end diffusion model*