Is ERA5 Fit for Purpose?

A Global Multi-Variable Evaluation of Reanalysis Strengths and Weaknesses

NC STATE

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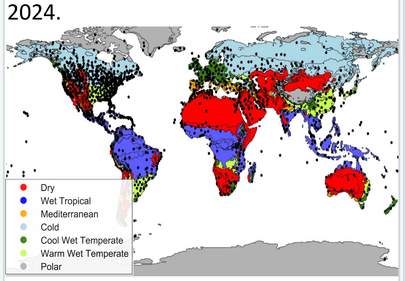
Motivation

Reanalysis products, such as the widely used ERA5, blend numerical weather model output with satellite, surface, and upper-air observations to produce gridded estimates of the atmospheric state. These products are extensively used as a proxy for observations in climate research, as initialization for weather models, and for AI training. However, reanalysis quality is not uniform, it varies by region, climate zone, meteorological variable, and time of day. Users often apply ERA5 without quantitative awareness of this varying data quality. Our goal is to assess the strengths and weaknesses of global reanalysis products compared to actual observations across diverse climate zones, seasonal and diurnal cycles, and weather conditions. This information will be useful to users to assess adequacy for purpose for their specific applications.

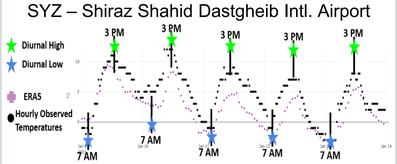
Data & Methods

We compare data from ECMWF ERA5 reanalysis to surface observations at 1200+ airport and buoy stations across the globe. We subset to the data into simplified Köppen-Geiger climate zones and calculate biases for the years 2019-2024.



To capture the diurnal cycle, we focus on 7 AM local time (near daily minimum temperature) and 3 PM local time (near daily maximum temperature). If there are no missing observations, a station has 365 x 2 x 2 =1460 yearly reanalysis-obs pairs.

SYZ – Shiraz Shahid Dastgheib Intl. Airport

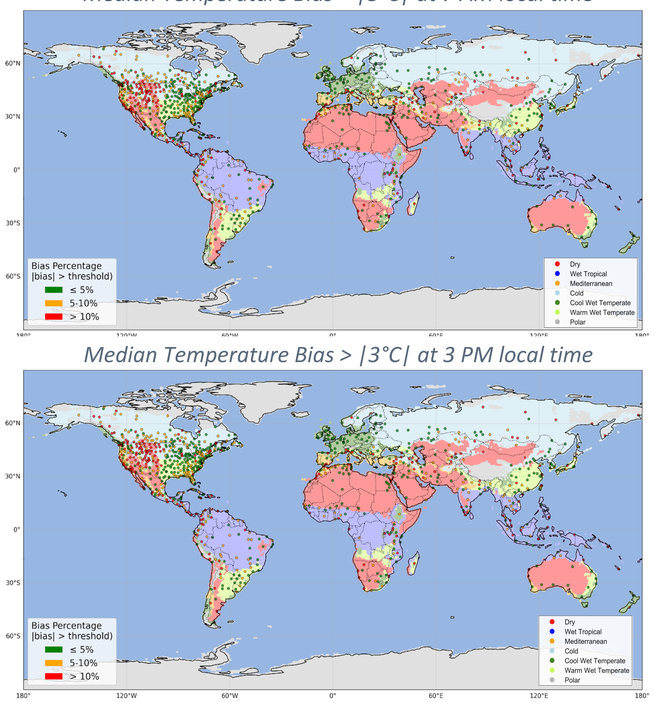


Time series plots showing reanalysis and observed temperature data in relation to our daily maximum (3 PM) and minimum (7 AM) time estimate

Temperature Biases at 7 AM and 3 PM

ERA5 temperature biases are generally small and well-centered near zero at both 7 AM and 3 PM across Temperate and Cold climate zones. Tropical, Dry, and Mediterranean zones exhibit the widest bias distributions at both 7 AM and 3 PM with biases exceeding +/- 3 °C greater than 10% of the time. The global map highlights that stations exceeding |3 °C| at 3 PM are concentrated in areas of complex terrain.

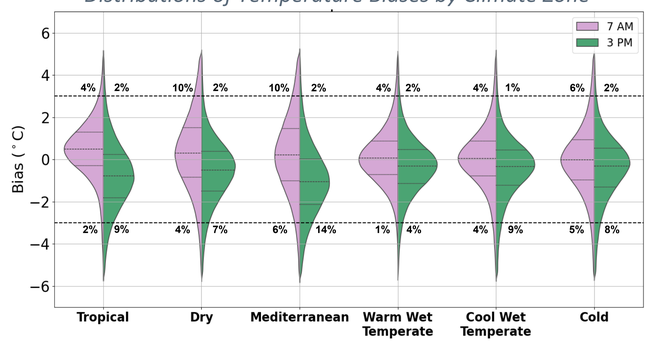
Median Temperature Bias > |3°C| at 7 AM local time



Median Temperature Bias > |3°C| at 3 PM local time

Global maps of land-based weather stations of the frequency of median ERA5 temperature bias exceeding |3°C| with station markers colored by the percentage of hours exceeding the threshold.

Distributions of Temperature Biases by Climate Zone

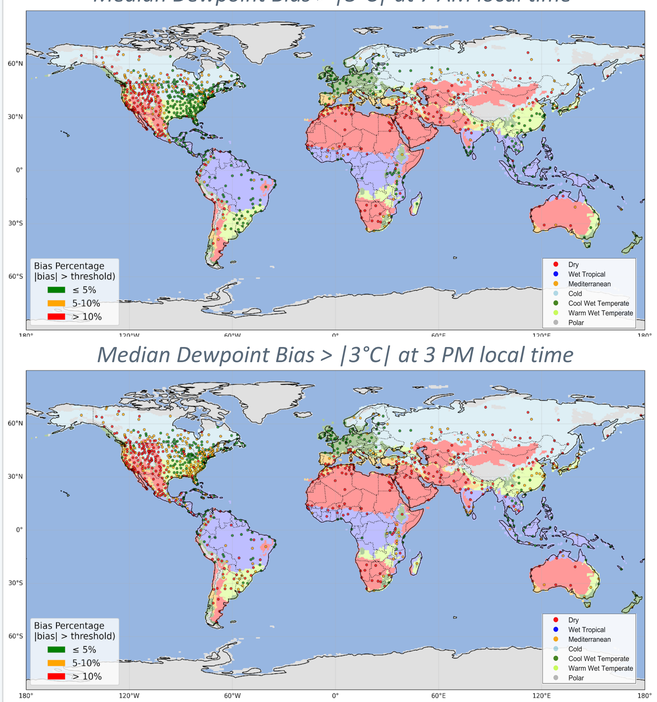


Distributions of ERA5 2-meter temperature biases (°C) at 7 AM (pink) and 3 PM (green) local time across climate zones. Distribution percentile values shown for > |3°C| bias thresholds (dashed lines).

Dewpoint Biases at 7 AM and 3 PM

ERA5 dewpoint performs poorly in Dry and Mediterranean zones, where biases exceed ±3°C roughly 18% of the time and afternoon biases are generally larger than morning biases. High-bias stations cluster in arid regions and complex terrain globally. Surface dewpoint errors of just 2°C can yield CAPE estimates that are in error by factor > 2 (see lower right), undermining ERA5's reliability as input for moisture-sensitive applications.

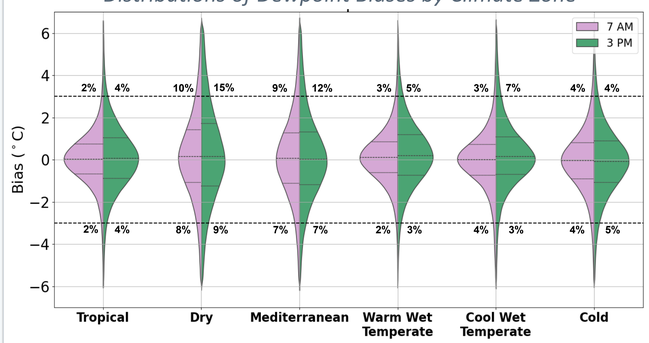
Median Dewpoint Bias > |3°C| at 7 AM local time



Median Dewpoint Bias > |3°C| at 3 PM local time

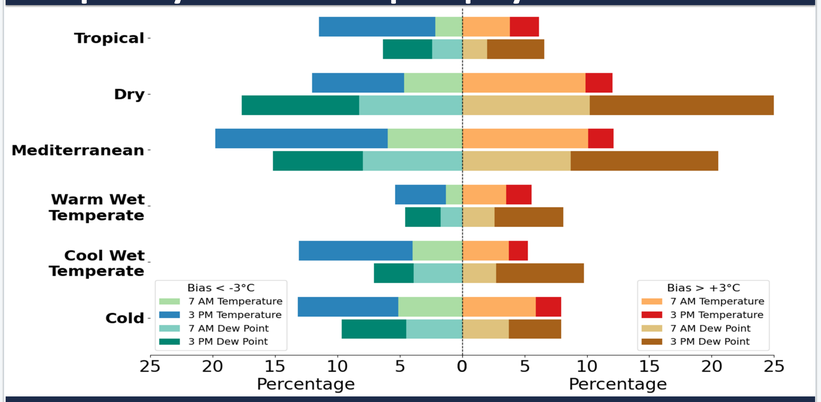
Global maps of land-based weather stations of the frequency of median ERA5 dewpoint bias exceeding |3°C| with station markers colored by the percentage of hours exceeding the threshold.

Distributions of Dewpoint Biases by Climate Zone

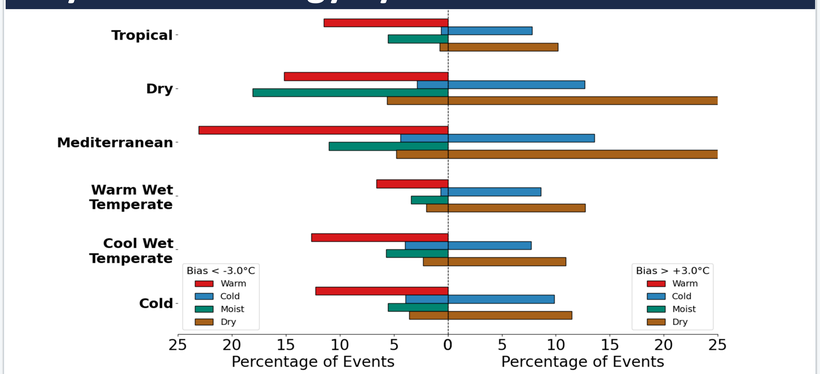


Distributions of ERA5 2-meter dewpoint biases (°C) at 7 AM (pink) and 3 PM (green) local time across climate zones. Distribution percentile values shown for > |3°C| bias thresholds (dashed lines).

Frequency of Biases > |3°C| by Climate Zone

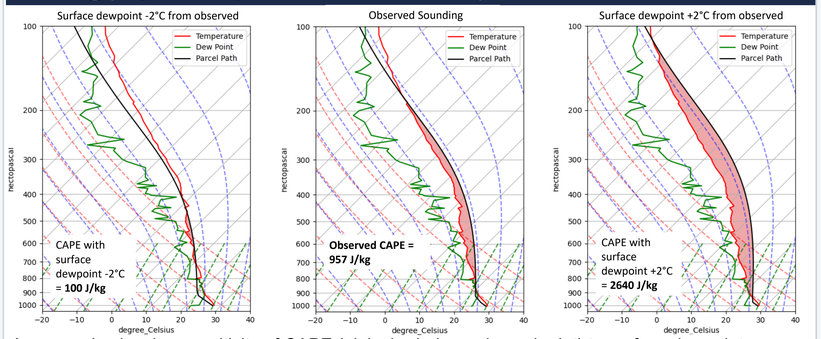


Frequency of > |3°C| Biases for Extreme Event Hours < 10th or > 90th percentile of a station's 30-year Climatology by Climate Zone



Stacked Horizontal Bar Plots of the frequency of temperature and dewpoint biases > |3°C| for extreme event hours. Extreme event conditions are generally underestimated by ERA5 across most climate zones at least 5% of the time. Warm events exhibit cold bias, Cold events exhibit warm bias, Moist events exhibit dry bias, and Dry events exhibit moist bias. Bias distributions are wider and more skewed in Tropical, Dry, and Mediterranean climate zones indicating more uncertainty and larger spread of errors in drier and warmer climate regimes. There are no hours where warm event errors are more than 3° higher in temperature and no hours where moist events errors are more than 3° higher in dewpoint.

Sensitivity of Convective Available Potential Energy (CAPE) to Small Dewpoint Errors



An example showing sensitivity of CAPE (pink shaded area in each plot) to surface dewpoints. Upper air sounding for Santarém, Pará, Brazil at 00 UTC on 2026 05 01. Weather conditions at this location was warm and humid with temperatures hovering around 29 °C with multiple rain showers and isolated thunderstorms in and around the vicinity.

Summary and Future Work

- Using 6 years of data, (2019-2024), we examine errors > |3°C| as of concern. Weather station temperature and dewpoint measurement uncertainty is about +/- 1°C.
- Biases (model – observations) at individual weather stations are generally larger for dewpoints than for temperatures.
- **Over ocean and in warm wet Temperate, cool wet Temperate, and Cold climate zones**, ERA5 matches well with temperature observations at 7 AM and 3 PM local times. Biases <-3°C or >3°C occur in ~10% of hours with larger errors in the afternoon as compared to the morning.
- More frequent biases <-3°C or >3°C for both temperature and dewpoint occur in complex terrain associated in part with representativity issues between weather station and ~30 km x ~30 km model grid.
- **For Dry and Mediterranean climate zones (arid regions), ~18% of time t**he dewpoint bias is <-3°C or >3°C with larger errors at 3 pm compared to 7 am.
- **Extreme events are often underestimated** in ERA5 reanalysis with more skewed bias distributions for Tropical, Dry, and Mediterranean as compared to Temperate and Cold climate zones. In particular, higher error frequencies occur in arid regions with > 90th percentile warm event hours as too cool and < 10th percentile dry events as too moist.
- Tendency for too moist dewpoints in arid environments appears to be a systematic problem.

Future work will extend the analysis back to 1995 to assess sensitivity to ENSO phase. These efforts will inform the development of a gridded ERA5 reliability product, providing users with guidance on ERA5 uncertainty in temperature and dewpoint.

Acknowledgments

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