README: Reproducibility Guide

1. Software and Versions Used

R Environment

- **R Version**: 4.3.1
- **Operating System**: Windows (tested on Windows, should work on macOS/Linux with path adjustments)

Required R Packages

The following packages are **required** for running the main reproducible analysis scripts (Theoretical.r and Case_studies.R):

```
# Install required packages with specific versions
install.packages("tidyverse")     # Version 2.0.0
install.packages("tidync")        # Version 0.3.0
```

Verified versions: The analysis was last tested and verified on April 28 with:

- `tidyverse` 2.0.0
- `tidync` 0.3.0

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2. Lines to Change for Different Machines

Functions.R

No changes required - this file contains only function definitions and does not reference external paths.

Theoretical.r

Line 2: Update the path to `Functions.R`

```
source("Functions.R")  # Change to absolute path if needed:
source("C:/your/path/Functions.R")
```

Case_studies.R

Line 2: Update the path to `Functions.R`

```
source("Functions.R")  # Change to absolute path if needed
```

Data-loading block near the top of the script: Update all NetCDF paths to match your local directory structure

```
era5_t2m <- tidync("C:/Users/leo/OneDrive - Uppsala universitet/Desktop/In
waiting/Fairness_AIFS_analysis/t2m_era5.nc")
AIFS_t2m_120 <- tidync("C:/Users/leo/OneDrive - Uppsala universitet/Desktop/In
waiting/Fairness_AIFS_analysis/AIFS_forecast_t2m_step_120.netcdf")
HRES_t2m_120 <- tidync("C:/Users/leo/OneDrive - Uppsala universitet/Desktop/In
waiting/Fairness_AIFS_analysis/HRES_forecast_t2m_step_120.netcdf")
era5_10u <- tidync("C:/Users/leo/OneDrive - Uppsala universitet/Desktop/In
waiting/Fairness_AIFS_analysis/10u_era5.nc")
era5_10v <- tidync("C:/Users/leo/OneDrive - Uppsala universitet/Desktop/In
waiting/Fairness_AIFS_analysis/10v_era5.nc")
AIFS_10u_120 <- tidync("C:/Users/leo/OneDrive - Uppsala universitet/Desktop/In
waiting/Fairness_AIFS_analysis/AIFS_forecast_u10_step_120.netcdf")
AIFS_10v_120 <- tidync("C:/Users/leo/OneDrive - Uppsala universitet/Desktop/In
waiting/Fairness_AIFS_analysis/AIFS_forecast_v10_step_120.netcdf")
HRES_10u_120 <- tidync("C:/Users/leo/OneDrive - Uppsala universitet/Desktop/In
waiting/Fairness_AIFS_analysis/HRES_forecast_u10_step_120.netcdf")
HRES_10v_120 <- tidync("C:/Users/leo/OneDrive - Uppsala universitet/Desktop/In
waiting/Fairness_AIFS_analysis/HRES_forecast_v10_step_120.netcdf")
```

Important: Update these paths to point to where you have stored the NetCDF data files on your machine.

2a. Functions.R - Core Functions

`Functions.R` contains all core functions used by both theoretical and empirical analyses:

Main Analysis Function

- `gen_skill_forecast()` - Generalized function for calculating forecast skill with compound penalties for consecutive missed extremes and mistrust penalties for consecutive false positives
  - Parameters include: probability of extreme, sensitivity/specificity, cost of missed extreme and protection, forecast price
  - Supports both theoretical (analytical) and simulated calculations
  - Supports compound penalty for missed extremes and mistrust penalty for false positives
  - In theoretical mode, run-based penalties are computed from an approximate expected number of runs with exact length `k`: `E[n_runs(k)] ≈ (n_obs - k + 1) * (1 - p)^2 * p^k`

Penalty Functions

- `penalty_geom(k, alpha=2)` - Geometric penalty function for missed extremes
- `mistrust_geom(k, alpha=2)` - Geometric mistrust penalty function for false positives
- `penalty_linear(k)` - Linear penalty function for missed extremes
- `mistrust_linear(k)` - Linear mistrust penalty function for false positives

Data Processing Functions

- `sel_points_city()` - Extract data from NetCDF files for a specific city and surrounding grid points
- `sel_points_city_10w()` - Extract 10m wind speed data (u and v components) from NetCDF files

Plotting Functions

- `make_no_penalty_plot()` - Generate comparison plots with no penalty
- `make_geom_alpha_comparison_plot()` - Generate comparison plots for geometric penalties with α=2 and α=4
- `make_linear_penalty_plot()` - Generate plots for linear penalties
- `plot_rev_curves_for_cities()` - Generate REV curves for multiple cities with summary statistics
- `get_baseline_from_results()` - Extract best baseline strategy from results

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3. Mapping of Outputs to Scripts

This section maps outputs to the scripts that create them.

Theoretical.r

This script generates all theoretical/simulation-based results using geometric and linear penalty functions:

Main Paper Figures:

- `min_accuracy_vs_probext_by_costratio_three_penalties_alpha_2.pdf` - Figure 1a: Minimum accuracy for positive REV vs. probability of extreme event (geometric α=2)
- `min_accuracy_vs_probext_by_costratio_three_penalties_alpha_4.pdf` - Figure 1b: Minimum accuracy for positive REV vs. probability of extreme event (geometric α=4)
- `tile_sens_spec_theor_0_REV_ratio_*.pdf` - Figure 2: Sensitivity vs. Specificity heatmaps (no penalty; one file per cost ratio)
- `tile_sens_spec_theor_0_REV_geom_ratio_*.pdf` - Figure 3a-b: Geometric compound penalty (α=2; one file per cost ratio)
- `tile_sens_spec_mistrust_geom_0_REV_ratio_*.pdf` - Figure 3c-d: Geometric mistrust penalty (α=2; one file per cost ratio)
- `tile_sens_spec_both_geom_0_REV_ratio_*.pdf` - Figure 3e-f: Both geometric penalties (α=2; one file per cost ratio)
- `tile_sens_spec_theor_0_REV_geom_a4_ratio_*.pdf` - Figure 4a-b: Geometric compound penalty (α=4; one file per cost ratio)
- `tile_sens_spec_mistrust_geom_a4_ratio_*.pdf` - Figure 4c-d: Geometric mistrust penalty (α=4; one file per cost ratio)
- `tile_sens_spec_both_geom_a4_ratio_*.pdf` - Figure 4e-f: Both geometric penalties (α=4; one file per cost ratio)

Appendix A (Theoretical Additional Results):

- `min_accuracy_vs_probext_by_costratio_three_penalties_linear.pdf` - Appendix A: Linear penalty comparison
- `tile_sens_spec_linear_penalty_ratio_*.pdf` - Appendix A: Linear compound penalty (one file per cost ratio)

- `tile_sens_spec_linear_mistrust_ratio_*.pdf` - Appendix A: Linear mistrust penalty (one file per cost ratio)
- `tile_sens_spec_linear_both_ratio_*.pdf` - Appendix A: Both linear penalties (one file per cost ratio)

Case_studies.R

This script generates all empirical/case study results using AIFS and HRES forecast data. Results are organized by geographic region (SEA = South Asia, SEU = Southern Europe) and variable (t2m = temperature, wind = 10m wind speed). Four quantile thresholds are used: q90 (default), q95, closest grid point analysis, and linear penalty variants.

Case Study Figures (PDF): Each analysis generates multiple PDFs with different penalty modes:

- `REV_{REGION}_{VAR}_{PENALTY_MODE}.pdf` - Analysis with specified penalty mode

Where:

- **REGION**: SEA_t2m, SEU_t2m, SEA_wind, SEU_wind (or variants: q95, closest, linear_*)
- **PENALTY_MODE**:
  - `no_penalty` - No penalty applied
  - `loss_geom_alpha_2_4` - Geometric compound penalty (α=2 and α=4 comparison)
  - `trust_geom_alpha_2_4` - Geometric mistrust penalty (α=2 and α=4 comparison)
  - `both_geom_alpha_2_4` - Both geometric penalties (α=2 and α=4 comparison)
  - `loss_linear` - Linear compound penalty
  - `trust_linear` - Linear mistrust penalty
  - `both_linear` - Both linear penalties

Main Paper Figures (q90 threshold):

- **Figure 5a-d**: South Asia temperature (t2m)
  - `REV_SEA_t2m_no_penalty.pdf`, `REV_SEA_t2m_loss_geom_alpha_2_4.pdf`, `REV_SEA_t2m_trust_geom_alpha_2_4.pdf`, `REV_SEA_t2m_both_geom_alpha_2_4.pdf`
- **Figure 6a-d**: Southern Europe temperature (t2m)
  - `REV_SEU_t2m_no_penalty.pdf`, `REV_SEU_t2m_loss_geom_alpha_2_4.pdf`, `REV_SEU_t2m_trust_geom_alpha_2_4.pdf`, `REV_SEU_t2m_both_geom_alpha_2_4.pdf`
- **Figure 7a-d**: South Asia 10m wind speed
  - `REV_SEA_wind_no_penalty.pdf`, `REV_SEA_wind_loss_geom_alpha_2_4.pdf`, `REV_SEA_wind_trust_geom_alpha_2_4.pdf`, `REV_SEA_wind_both_geom_alpha_2_4.pdf`
- **Figure 8a-d**: Southern Europe 10m wind speed
  - `REV_SEU_wind_no_penalty.pdf`, `REV_SEU_wind_loss_geom_alpha_2_4.pdf`, `REV_SEU_wind_trust_geom_alpha_2_4.pdf`, `REV_SEU_wind_both_geom_alpha_2_4.pdf`

Appendix A Figures (Linear Penalty Variants):

- `REV_SEA_t2m_loss_linear.pdf`, `REV_SEA_t2m_trust_linear.pdf`, `REV_SEA_t2m_both_linear.pdf`
- `REV_SEU_t2m_loss_linear.pdf`, `REV_SEU_t2m_trust_linear.pdf`, `REV_SEU_t2m_both_linear.pdf`
- `REV_SEA_wind_loss_linear.pdf`, `REV_SEA_wind_trust_linear.pdf`, `REV_SEA_wind_both_linear.pdf`
- `REV_SEU_wind_loss_linear.pdf`, `REV_SEU_wind_trust_linear.pdf`, `REV_SEU_wind_both_linear.pdf`

Appendix B Figures (q95 threshold):

- `REV_SEA_t2m_q95_*.pdf`, `REV_SEU_t2m_q95_*.pdf`, `REV_SEA_wind_q95_*.pdf`, `REV_SEU_wind_q95_*.pdf` - Analysis with 95th percentile threshold for all penalty modes

Appendix C Figures (Closest Grid Point Analysis):

- `REV_SEA_t2m_closest_*.pdf`, `REV_SEU_t2m_closest_*.pdf`, `REV_SEA_wind_closest_*.pdf`, `REV_SEU_wind_closest_*.pdf` - Using single closest grid point instead of averaging neighboring cells

Appendix D Tables:

- These four q90 summary CSV exports are the table outputs available from `Case_studies.R` and can be used for appendix table reporting.

Summary Tables (CSV):

- `result_SEA_summary.csv` - q90 baseline summary table (SEA temperature)
- `result_SEU_summary.csv` - q90 baseline summary table (SEU temperature)
- `result_SEA_wind_summary.csv` - q90 baseline summary table (SEA wind)
- `result_SEU_wind_summary.csv` - q90 baseline summary table (SEU wind)

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4. Guidance for Reviewers

Running Order

The scripts can be run independently, but we recommend the following order:

1. **First**: Ensure `Functions.R` is in your working directory and install the required packages.
2. **Run `Theoretical.r`**: Generates all theoretical results (no data files needed)
    - Runtime: ~5-15 minutes depending on machine

- Generates multiple PDFs showing theoretical analyses with different penalty functions (geometric and linear, α=2 and α=4)

3. **Run `Case_studies.R`**: Generates all empirical results (requires NetCDF data files included in the reproducibility package)
    - Runtime: ~20-60 minutes depending on machine and data size

- Generates many PDFs and 4 CSV summary tables covering multiple geographic regions, variables, quantile thresholds, and penalty modes

Output Summary

- **Theoretical.r outputs**:
  - Multiple PDF files with sensitivity/specificity heatmaps and minimum accuracy curves
  - Analysis includes geometric penalties (α=2 and α=4), linear penalties, and no-penalty baseline
  - Multiple cost-loss ratios (0.01, 0.05, 0.1, 0.2) for fully parameterized results
- **Case_studies.R outputs**:
  - Many PDF files organized by geographic region (SEA/SEU), variable (t2m/wind), analysis type (q90/q95/closest), and penalty mode
  - 4 CSV files with summary statistics (one per region-variable combination)
  - Each analysis compares multiple penalty functions and their effects on forecast economics

Key Notes

1. **Working Directory**: All scripts assume output files will be saved in the current working directory. Set your working directory using:

```
setwd("C:/your/desired/output/directory")
```

2. **NetCDF Data**: The NetCDF files referenced in `Case_studies.R` are large (typically several GB total). Ensure you have:
   - Downloaded all required NetCDF files from the data repository
   - Sufficient disk space (~5-10 GB for data + outputs)

- Updated the NetCDF file paths in the data-loading block at the top of `Case_studies.R`

3. **Memory Requirements**:
   - `Theoretical.r`: Requires ~2-4 GB RAM
   - `Case_studies.R`: Requires ~8-16 GB RAM due to large NetCDF files
   - Processing time scales with data size and number of cities analyzed
4. **Penalty Functions**:
   - **Geometric penalties**: Applied as multiplicative factors to base costs (α determines severity)
   - **Linear penalties**: Applied as additive factors to base costs
   - **Compound penalty**: Penalizes consecutive missed extremes (false negatives)
   - **Mistrust penalty**: Penalizes consecutive false positives to maintain trust in the forecast

- **Theoretical run-count approximation**: The analytical branch in `gen_skill_forecast()` uses an exact-run approximation for length `k` runs, `E[n_runs(k)] ≈ (n_obs - k + 1)(1-p)^2p^k`

5. Data Availability

All data necessary for the analysis were included in the reproducibility package provided to the WB. All data are produced by ECMWF and covered by a CC-BY-4.0 licence.

Data Coverage and Surface Variables

- **ERA5 file coverage**: 2024-02-28 00:00 to 2025-03-15 18:00 UTC
- **AIFS step-120 valid-time coverage**: 2024-03-04 12:00 to 2025-03-06 12:00 UTC
- **IFS HRES step-120 valid-time coverage**: 2024-03-04 00:00 to 2025-03-06 12:00 UTC
- **AIFS step-120 initialization coverage**: 2024-02-28 12:00 to 2025-03-01 12:00 UTC (5 days earlier than valid time)
- **IFS HRES step-120 initialization coverage**: 2024-02-28 00:00 to 2025-03-01 12:00 UTC (5 days earlier than valid time)
- **Forecast Lead Time**: 5 days ahead (Step 120 in forecast notation)
- **Alignment note**: Verification is done at common valid times (AIFS/HRES step-120 valid time matched to ERA5 time), so no additional manual 5-day shift is applied in the join.
- **Example**: A forecast initialized on 2024-02-28 verifies at valid time 2024-03-04 (step 120), and is matched to ERA5 at 2024-03-04.

Surface Variables Used

The analysis uses the following surface variables from all three data sources (ERA5, AIFS, and IFS HRES):

1. **Temperature at 2 meters (t2m)**
    - ERA5: variable name `2t`
    - AIFS forecast (step 120): variable name `t2m`
    - IFS HRES forecast (step 120): variable name `t2m`
2. **10-meter Wind Components (u10, v10)**
    - ERA5: variable names `10u` and `10v`
    - AIFS forecast (step 120): variable names `u10` and `v10`
    - IFS HRES forecast (step 120): variable names `u10` and `v10`

Data Sources

- **ERA5**: Reference/observation dataset from Copernicus Climate Data Store
- **AIFS**: AI-based forecast system at step 120 (5-day lead time)
- **IFS HRES**: Deterministic forecast from ECMWF's Integrated Forecasting System (High Resolution) at step 120 (5-day lead time)

Data source: ERA5 Reanalysis Data

ERA5 reanalysis data are publicly available and were retrieved through the Copernicus Climate Data Store:

Dates and times in the ERA5 file: 2024-02-28 00:00 to 2025-03-15 18:00 UTC. **Timestamps used for forecast verification:** 00:00 and 12:00 UTC, matched to step-120 forecast valid times.

Citation: Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., Nicolas, J., Peubey, C., Radu, R., Schepers, D., Simmons, A., Soci, C., Abdalla, S., Abellan, X., Balsamo, G., Bechtold, P., Biavati, G., Bidlot, J., Bonavita, M., De Chiara, G., Dahlgren, P., Dee, D., Diamantakis, M., Dragani, R., Flemming, J., Forbes, R., Fuentes, M., Geer, A., Haimberger, L., Healy, S., Hogan, R.J., Hólm, E., Janisková, M., Keeley, S., Laloyaux, P.,

Lopez, P., Lupu, C., Radnoti, G., de Rosnay, P., Rozum, I., Vamborg, F., Villaume, S., and Thépaut, J.-N. (2020): The ERA5 global reanalysis. *Quarterly Journal of the Royal Meteorological Society*, 146(730), 1999-2049. https://doi.org/10.1002/qj.3803

DOI: 10.24381/cds.adbb2d47

Access: https://cds.climate.copernicus.eu/datasets/reanalysis-era5-single-levels?tab=download

Last accessed: 2025

Data Source: AIFS and IFS HRES Forecast Data

AIFS and IFS HRES forecast data are publicly available and were retrieved through the ECMWF MARS (Meteorological Archival and Retrieval System) server:

Dates used in this analysis:

- AIFS valid times: 2024-03-04 12:00 to 2025-03-06 12:00 UTC (step 120)
- IFS HRES valid times: 2024-03-04 00:00 to 2025-03-06 12:00 UTC (step 120)
- AIFS initialization times: 2024-02-28 12:00 to 2025-03-01 12:00 UTC (5 days earlier)
- IFS HRES initialization times: 2024-02-28 00:00 to 2025-03-01 12:00 UTC (5 days earlier)

Access: AIFS: https://apps.ecmwf.int/mars-catalogue/?model=aifs-single&type=fc&class=ai&stream=oper&expver=1 IFS HRES: https://apps.ecmwf.int/mars-catalogue/?type=fc&class=od&stream=oper&expver=1

Last accessed: 2025

Note: Access to MARS data may require an ECMWF account and member state data access permissions.

Last Updated: April 28, 2026