# Supplementary material

**Table S1.** Terrain and land cover characteristics of ERA5 grid points falling within a 0.25-deg buffer from each site's location [1].

| Tall towers | | ERA5 grid points | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Lat (deg N) | Long (deg E) | # | Lat (deg N) | Long (deg E) | Distance from tower (km) | Altitude (m a.s.l.) | | Surface roughness length (m) | Low vegetation | | High vegetation | |
| | | | | | | μ | σ | | Cover (%) | Category | Cover (%) | Category |
| FINO3 | | | | | | | | | | | | |
| 55.19 | 7.16 | | | | | | | | | | | |
| | | 1 | 55.25 | 7.00 | 12.149 | < 0 | | 0.0 | 100 | Sea | | |
| | | 2 | 55.00 | 7.00 | 23.458 | < 0 | | 0.0 | 100 | Sea | | |
| | | 3 | 55.25 | 7.25 | 8.783 | < 0 | | 0.0 | 100 | Sea | | |
| | | 4 | 55.00 | 7.25 | 21.895 | < 0 | | 0.0 | 100 | Sea | | |
| Cabauw | | | | | | | | | | | | |
| 51.97 | 4.93 | | | | | | | | | | | |
| | | 1 | 52.00 | 4.75 | 12.774 | -1 | 2 | 0.3 | 90 | Crops and mixed farming | 10 | Interrupted forest |
| | | 2 | 52.00 | 5.00 | 5.842 | -1 | 3 | 0.3 | 90 | Crops and mixed farming | 10 | Interrupted forest |
| | | 3 | 51.75 | 5.00 | 24.938 | 2 | 3 | 0.4 | 90 | Crops and mixed farming | 10 | Interrupted forest |
| Boulder | | | | | | | | | | | | |
| 39.91 | -105.23 | | | | | | | | | | | |
| | | 1 | 40.00 | -105.25 | 10.155 | 2026 | 190 | 0.5 | 90 | Short grass | 10 | Deciduous broadleaf trees |
| | | 2 | 39.75 | -105.25 | 17.878 | 2131 | 161 | 0.6 | 80 | Short grass | 20 | Deciduous broadleaf trees |
| | | 3 | 40.00 | -105.00 | 22.017 | 1623 | 108 | 0.1 | 90 | Short grass | 10 | Deciduous broadleaf trees |
| Ghoroghchi | | | | | | | | | | | | |
| 33.59 | 51.00 | | | | | | | | | | | |
| | | 1 | 33.75 | 51.00 | 17.796 | 2019 | 194 | 0.0 | 70 | Semidesert | | |
| | | 2 | 33.50 | 51.00 | 10.010 | 2065 | 101 | 0.0 | 70 | Semidesert | | |
| Humansdorp | | | | | | | | | | | | |
| -34.11 | 24.51 | | | | | | | | | | | |
| | | 1 | -34.00 | 24.50 | 12.270 | 206 | 68 | 0.1 | 90 | Short grass | 10 | Deciduous broadleaf trees |
| | | 2 | -34.25 | 24.50 | 15.599 | 39 | 23 | 0.2 | 20 | Crops and mixed farming | 60 | Interrupted forest |
| Wallaby Creek | | | | | | | | | | | | |
| -37.43 | 145.19 | | | | | | | | | | | |
| | | 1 | -37.50 | 145.00 | 18.493 | 260 | 52 | 0.5 | 70 | Crops and mixed farming | 30 | Interrupted forest |
| | | 2 | -37.25 | 145.25 | 20.712 | 334 | 112 | 0.7 | 40 | Crops and mixed farming | 60 | Interrupted forest |
| | | 3 | -37.50 | 145.25 | 9.417 | 339 | 125 | 1.6 | | | 100 | Evergreen broadleaf trees |

[1] ECMWF low/high vegetation types considered as land cover categories [49].

[2] Locations' maps of mean altitude and roughness length are presented in Figures S1 and Figures S2, respectively.

**Table S2.** Statistical values of annual air density observed vs. estimated by ERA5 at the six towers [1].

| Height (m) | N (%) | Observations | | Estimations | | Statistical indicators | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | $\mu_o$ (kg/m³) | $\sigma_o$ (kg/m³) | $\mu_p$ (kg/m³) | $\sigma_p$ (kg/m³) | MB (kg/m³) | NB | RMSE (kg/m³) | NRMSE | r |
| FINO3 | | | | | | | | | | |
| 60 | 15815 (90.27) | 1.235 | 0.026 | 1.235 | 0.022 | 0.000 | 0.00 | 0.014 | 0.01 | 0.85 |
| 100 | 15439 (88.12) | 1.231 | 0.023 | 1.230 | 0.022 | 0.001 | 0.00 | 0.004 | 0.00 | 0.98 |
| Cabauw | | | | | | | | | | |
| 40 | 17512 (99.95) | 1.232 | 0.097 | 1.239 | 0.028 | -0.007 | -0.01 | 0.095 | 0.08 | 0.21 |
| 80 | 17511 (99.95) | 1.174 | 0.313 | 1.234 | 0.028 | -0.060 | -0.05 | 0.313 | 0.26 | 0.28 |
| Boulder | | | | | | | | | | |
| 50 | 17321 (98.86) | 0.994 | 0.041 | 0.986 | 0.036 | 0.007 | 0.01 | 0.032 | 0.03 | 0.68 |
| 80 | 17321 (98.86) | 0.990 | 0.041 | 0.984 | 0.036 | 0.007 | 0.01 | 0.032 | 0.03 | 0.68 |
| Ghoroghchi | | | | | | | | | | |
| 60 | 6267 (71.54) | 0.935 | 0.037 | 0.952 | 0.038 | -0.017 | -0.02 | 0.039 | 0.04 | 0.55 |
| 100 | 6267 (71.54) | 0.932 | 0.037 | 0.949 | 0.038 | -0.017 | -0.02 | 0.039 | 0.04 | 0.55 |
| Humansdorp | | | | | | | | | | |
| 60 | 8758 (99.70) | 1.201 | 0.021 | 1.194 | 0.020 | 0.006 | 0.01 | 0.011 | 0.01 | 0.90 |
| Wallaby Creek | | | | | | | | | | |
| 95 | 4741 (54.12) | 1.133 | 0.025 | 1.191 | 0.031 | -0.058 | -0.05 | 0.060 | 0.05 | 0.91 |

N (%): number of observations/predictions (valid data percent); $\mu_o$: mean of observations; $\sigma_o$: standard deviation of observations; $\mu_p$: mean of predictions; $\sigma_p$: standard deviation of predictions; MB: mean bias; NB: normalised bias; RMSE: root mean square error; NRMSE: normalised root mean square error; r: correlation coefficient.

[1] For each site, time periods as in Table 2 have been considered.

**Table S3.** WT power losses (%) accounted for by WT system and cause/component [1] [20].

| WT system | Gearbox | Generator | Converter | Unavailab. & repair | Total |
|---|---|---|---|---|---|
| | $f_{gearbox}$ | $f_{generator}$ | $f_{converter}$ | $f_{unavailability}$ | $F_{WT}$ |
| A: fixed-speed | 4.0 | 2.5 | 0.0 | 0.2 | 6.59 |
| B: variable-speed with induction generator | 3.0 | 2.2 | 2.4 | 1.4 | 8.71 |
| C: variable-speed with doubly fed induction generator | 3.0 | 1.5 | 0.8 | 1.2 | 6.36 |
| D: variable-speed with direct-drive synchronous generator | 0.0 | 3.5 | 4.7 | 0.1 | 8.13 |

[1] WT-specific total losses ($F_{WT}$) calculated based on Eq. (10).

**Table S4.** WT power losses (%) accounted for by site [1].

| Site | Electric grid connection | Ice | Other | Total by site |
|---|---|---|---|---|
| | $f_{grid}$ | $f_{ice}$ | $f_{other}$ | $F_{site}$ |
| FINO3 | 2.0 | 3.0 | 0.0 | 4.94 |
| Cabauw | 1.0 | 3.0 | 0.0 | 3.97 |
| Boulder | 1.0 | 4.0 | 0.0 | 4.96 |
| Ghoroghchi | 4.0 | 0.0 | 0.0 | 4.00 |
| Humansdorp | 2.0 | 0.0 | 0.0 | 2.00 |
| Wallaby Creek | 2.0 | 4.0 | 0.0 | 5.92 |

[1] Site-specific total losses ($F_{site}$) calculated based on Eq. (11).

**Table S5.** WT power losses (%) accounted for by site and height-related air density [1,2].

| Site | Total losses by site | Height (m) | Air density losses (or gains) vs. air density standard value | | Total losses by site and air density | |
|---|---|---|---|---|---|---|
| | | | Observed | Estimated | Observed | Estimated |
| FINO3 | 4.94 | 60 | –0.82 | –0.82 | 4.16 | 4.16 |
| | | 100 | –0.49 | –0.41 | 4.47 | 4.55 |
| Cabauw | 3.97 | 40 | –0.57 | –1.14 | 3.42 | 2.87 |
| | | 80 | 4.16 | –0.73 | 7.97 | 3.26 |
| Boulder | 4.96 | 50 | 18.86 | 19.51 | 22.88 | 23.50 |
| | | 80 | 19.18 | 19.67 | 23.19 | 23.66 |
| Ghoroghchi | 4.00 | 60 | 23.67 | 22.45 | 26.73 | 25.55 |
| | | 100 | 23.92 | 22.45 | 26.96 | 25.55 |
| Humansdorp | 2.00 | 60 | 1.96 | 2.86 | 3.92 | 4.80 |
| Wallaby Creek | 5.92 | 95 | 7.51 | 2.86 | 12.99 | 8.61 |

[1] For each site, height-related air density losses (or gains) ($F_\rho$) have been calculated based on considering the difference of observed and estimated annual mean values reported in Table S2 with respect to air density standard value (1.225 kg/m$^3$).

[2] Total losses by site and height-related air density have been calculated as: $F_{site\ \&\ \rho} = 1 - [(1- F_{site})(1- F_\rho)]$.

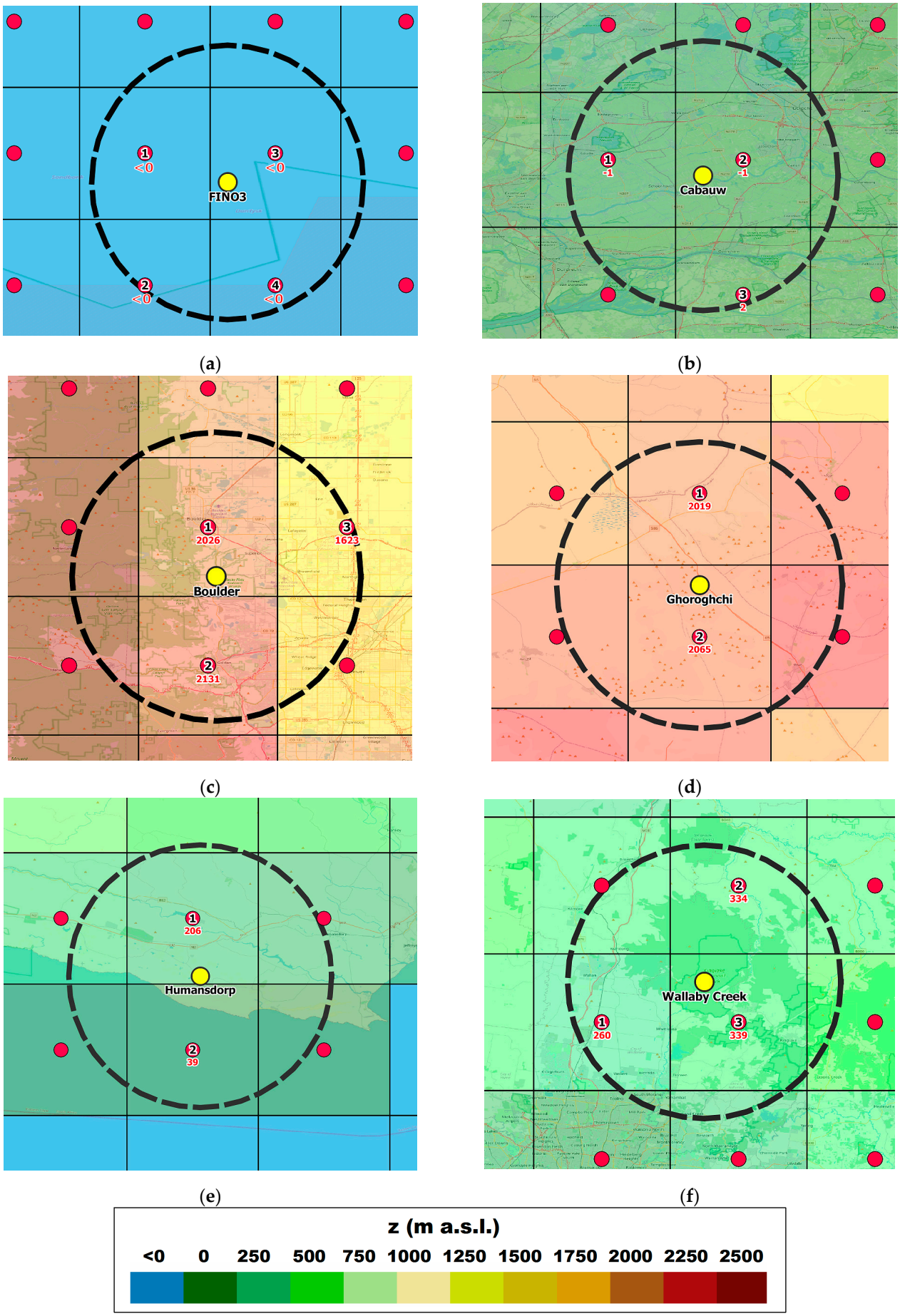


**Figure S1**. Mean altitude (m) of ERA5 grid points closest to each tower's location: (**a**) FINO3; (**b**) Cabauw; (**c**) Boulder; (**d**) Ghoroghchi; (**e**) Humansdorp; (**f**) Wallaby Creek. The values of grid points within a 0.25-deg buffer from towers (shown as black dashed circle) are also reported. Cartography basemap: OpenStreetMap.

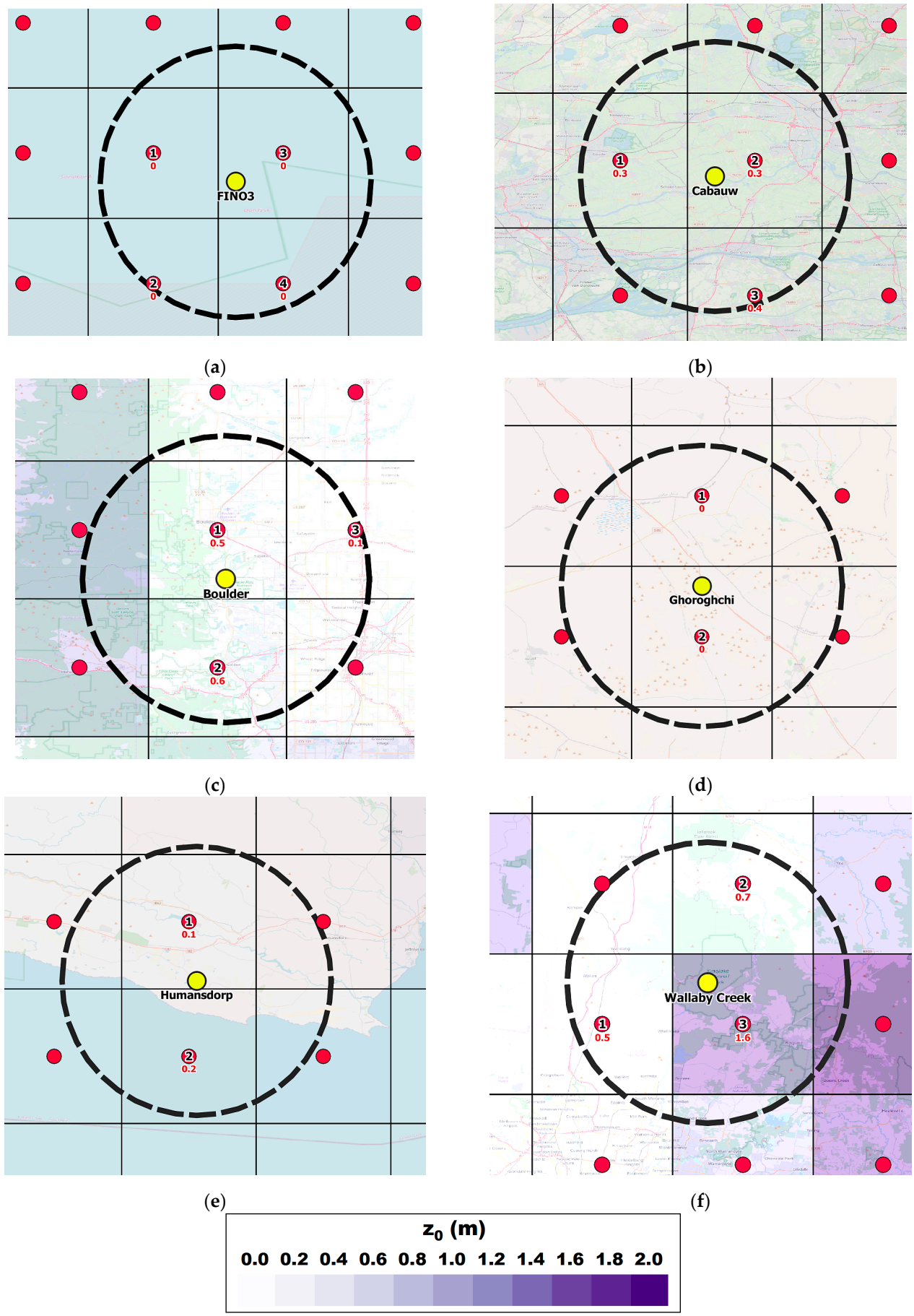


**Figure S2**. Mean roughness length (m) of ERA5 grid points closest to each tower's location: (**a**) FINO3; (**b**) Cabauw; (**c**) Boulder; (**d**) Ghoroghchi; (**e**) Humansdorp; (**f**) Wallaby Creek. The values of grid points within a 0.25-deg buffer from towers (shown as black dashed circle) are also reported. Cartography basemap: OpenStreetMap.

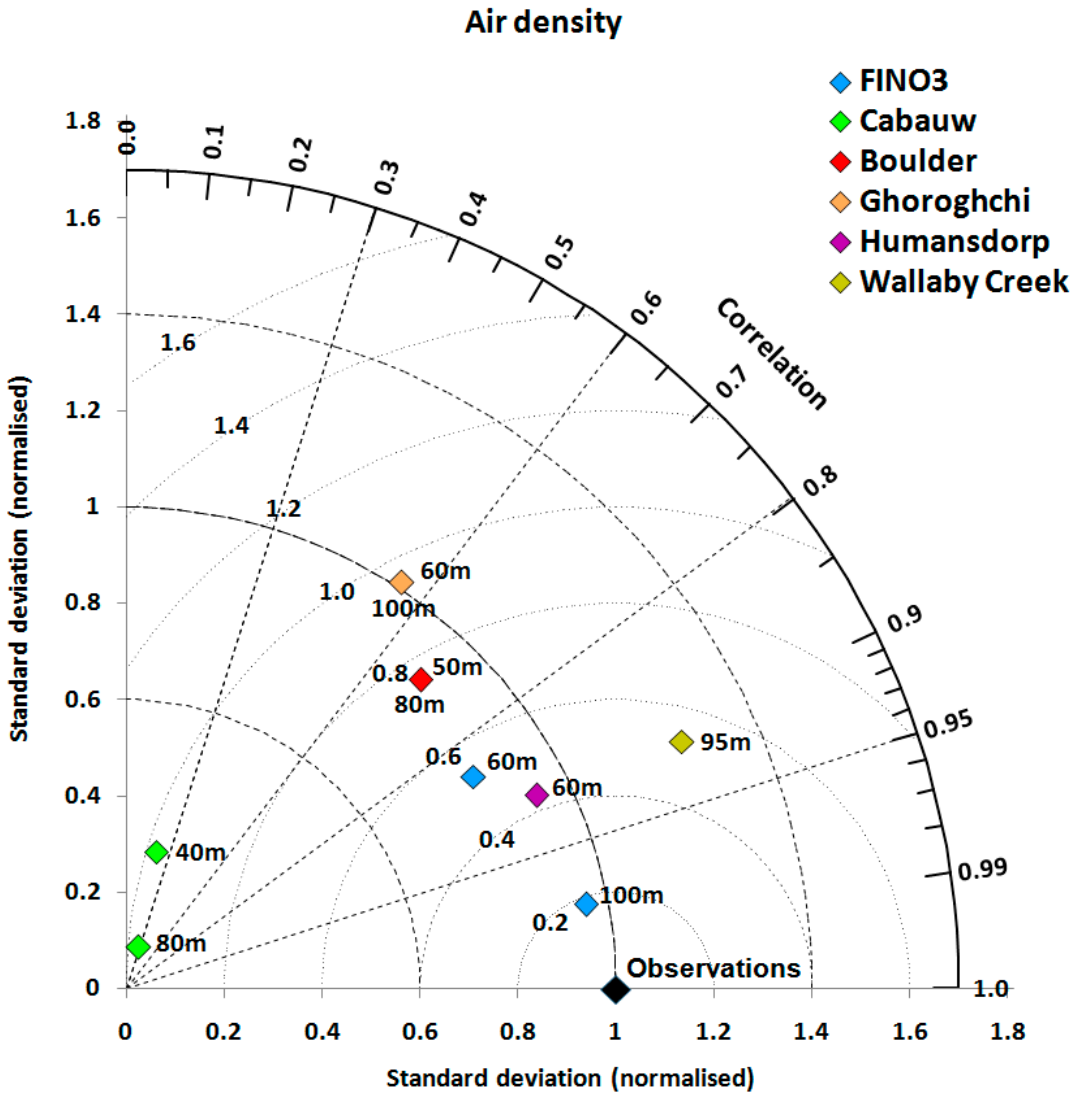


**Figure S3.** Taylor diagram of annual average air density predicted by height by ERA5 reanalysis data at the six study locations. Standard deviations of predictions ($\sigma_P$) and RMSD (proportional to the radial distance from observations) are normalised by the standard deviation of observations ($\sigma_O$).