

It Rains Because the Washing Is Out:

Household Line-Drying as the Controlling Moisture Source for Warm-Season Rainfall, with a Cluster-Randomised Trial in 3,214 Homes

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(84 clusters, six national grids)

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Abstract

It rains as soon as the washing goes out. The washing is the reason. A load hung outside releases about 2.1 kg of water into the air just above the ground, in the hours when that air decides whether a cloud will form, and nothing else people do puts water there. The total is trivial — four hundredths of one per cent of the seasonal moisture budget — and total water is not what governs convective initiation. Household drying can be read off the electricity meter: a wash cycle with no dryer cycle behind it is a load on a line. We reconstructed ten years of it for 1.42 million homes and tested it four ways. Clusters supplied with tumble dryers in a two-season cluster-randomised trial rained less than clusters left on the line. The same step appears wherever a right-to-dry statute commences, and again when a dryer breaks. Pooling the three, we attribute 0.36 of warm-season rain-hours over inhabited land to domestic drying (95% CI 0.32–0.41). Rain re-wets the line and the line is re-hung, so the mechanism is a loop; in the temperate maritime zone its gain is 1.07. A loop with gain above one and a delay does not settle. Weather is not something that happens to the washing.

Keywords: boundary-layer moisture; line drying; convective initiation; weekly precipitation cycle; forecast skill attribution

1 Introduction

Domestic line-drying is the largest single source of the water that decides whether it rains over an inhabited place. It is not the largest source of water. That distinction is the subject of this paper.

The complaint is old and everywhere. People hang out washing, it rains, and they say so. The remark has

been filed as a joke about human self-regard (Hallward, 2009). It has never been tested. The reason it has never been tested is not that anyone examined it and found it wanting; it is that the exposure could not be measured. Nobody knows what a country dried outdoors last Tuesday, and surveys of the question do not survive validation (Ostrowska, 2015).

We take the objection to the claim seriously, and we state it before anyone else does. A washing line is a trivial hydrological object. Across a mid-latitude country of 22.6 million households, an entire warm season of outdoor drying releases 3.8 Tg of water, against a seasonal moisture budget above 9,000 Tg. That is 0.04%. On any total-water accounting the effect of laundry on rainfall is not small; it is absent.

Total water does not initiate convection. A parcel of surface air either reaches its level of free convection during the heating of the day or it does not, and near that margin the outcome turns on the last few tenths of a gram per kilogram in the lowest tens of metres (Tetzlaff, 1998; Marren and Ojukwu, 2011). The relevant term is not how much water a landscape holds. It is how much water is delivered below the mixing height, in the four hours before the boundary layer tops out. Almost nothing puts water there. Transpiration is delivered through a canopy into a mixed layer already several hundred metres deep by mid-morning; open water is offshore or in the wrong place; advected marine moisture arrives aloft and takes a day to mix down. In that budget, a wet sheet on a line at ten in the morning is a large term.

This paper reports four independent tests of that claim and one model that reconciles them.

We first describe an instrument. Household drying leaves a signature in domestic electricity metering: a completed wash cycle with no dryer cycle behind it is a wet load that went somewhere. We call it the wash-without-dry residual, and we have ten years of it for 1.42 million metered homes.

We then test the exposure against precipitation four

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ways, chosen because they fail for different reasons. The weekly cycle in rainfall, long attributed to week-day aerosol (Cerveny and Halstead, 2003; Ibarra et al., 2017), has the right amplitude and the wrong phase; drying has the right phase, and leads rain by 6.4 hours. A two-season cluster-randomised trial supplied 42 clusters with tumble dryers and left 42 on the line. Nineteen jurisdictions commenced right-to-dry statutes on dated orders, which is an exogenous increase in line use with no meteorological accompaniment. And tumble dryers break, which pushes a household outdoors for the length of a repair.

Finally, we audit the discipline. Twenty-four-hour precipitation forecast skill over inhabited land has not improved since 1991, through a roughly million-fold increase in computing and a forty-fold increase in resolution, while skill over ocean and over uninhabited land improved throughout. A system whose output does not respond to a million-fold improvement in one component was never limited by that component. We show what the constraint was, and what happens to the flat line when it is relieved.

2 A large literature about the wrong term

The weekly cycle in precipitation is real and well described. Gauge records on four continents show warm-season rain-hours elevated at the end of the week and suppressed at its start, with an amplitude between 5% and 9% (Cerveny and Halstead, 2003). The standard account is aerosol: particulate loading accumulates through the working week, seeds condensation, and rains out (Ibarra et al., 2017). The account is physically sound and the amplitude it predicts is approximately correct.

Its difficulty is the phase. Aerosol loading in the six national inventories we examined peaks on Wednesday. The rain-hour anomaly peaks between Sunday afternoon and Sunday night. The discrepancy has been noted (Delacroix, 2020; Ibarra and Sandoval, 2021), attributed variously to residence time and to weekend industrial scheduling, and left there. A mechanism that predicts the size of an effect but misses its timing by three days is not an explanation of that effect.

The boundary-layer literature is where our mechanism comes from, and we use it as written. Tetzlaff (1998) established the sensitivity of convective inhibition to sub-cloud mixing ratio, and Marren and Ojukwu (2011) showed that near the initiation margin the derivative is steep enough that changes below the detection limit of the operational radiosonde network are sufficient to switch a day between convecting and not. Neither author considered domestic sources. There was no reason to: the term had never been measured, so it did not appear in any budget, so nobody looked

for it.

That is the ordinary way a term goes missing. It is not suppressed. It is simply not on the instrument.

3 The exposure: the wash-without-dry residual

3.1 Construction

Domestic smart meters in the six grids we accessed sample at 1 Hz and retain appliance-level disaggregation for regulatory purposes (Grid Metering Council, 2019). A washing machine cycle is unmistakable: a motor ramp, a resistive heating plateau, and a terminal sequence of spin transients at 800–1600 rpm. A tumble dryer is equally unmistakable: sustained resistive draw, near-constant for 40–70 minutes, with no spin signature.

The wash-without-dry residual (WWD) is a completed wash cycle not followed by a dryer cycle in the same dwelling within 90 minutes. The load left the machine wet. In a dwelling there are three places for it to go — a line, an airer, or a radiator — and only the line is outdoors.

3.2 Calibration

We fitted 4,102 households with a door-frame optical counter on the drying-line access, and 260 of those with a roof-mounted time-lapse camera at 6-minute cadence. Against observed line loads, WWD classification achieved a sensitivity of 0.94, a specificity of 0.91, and $\kappa = 0.86$ (Supplementary Register, Table S4).

3.3 What the instrument cannot do

It cannot distinguish a washing line from an indoor airer. Both are a wash with no dryer behind it, and at the meter they are the same event. From the camera sub-cohort we estimate that 14.1% of WWD events are indoor. Indoor drying delivers its water above the floor of a heated dwelling and, on our own mechanism, should do nothing at all. Misclassification is therefore non-differential with respect to outcome, and attenuates every estimate in this paper towards the null. We have not corrected for it.

4 A budget in which our term is a rounding error

Table 1 gives the warm-season moisture budget for the inhabited grid cells of the reference country. We measured retained water gravimetrically on 2,340 loads across four spin speeds: mean 2.14 kg per load (SD 0.31), consistent with the appliance standard (International Electrotechnical Commission, 2014). Households dry 4.1 loads per week outdoors and a further 2.6 in a vented machine (National Statistical Office, 2023); over

a nineteen-week season and 22.6 million households, outdoor drying releases 3.8 Tg.

Our term is three orders of magnitude below the largest in the table, and one term is smaller still. That is the point.

The final column of Table 1 gives each term's share of the water delivered below 50 m between 09:00 and 13:00 local — the layer and the window in which the sub-cloud mixing ratio is set for the day. Transpiration is largely absent from it, because by mid-morning it is being mixed through several hundred metres of depth. Marine advection is absent because it arrives above the inversion. Open-water evaporation is absent because it is not where people are. Domestic outdoor drying is 61.0% of that column, and it is there because people hang washing out in the morning so that it will be dry by the evening.

The sensitivity that makes this consequential is not ours. Writing q for the mean mixing ratio of the sub-cloud layer and CIN for convective inhibition, Marren and Ojukwu (2011) report

$$\frac{\partial \text{CIN}}{\partial q} = -\alpha \frac{g}{\theta_v} \int_{z_0}^{z_{\text{LFC}}} \frac{\partial \theta_v}{\partial q} dz, \quad \alpha = 1.9 \pm 0.2, \quad (1)$$

with the practical consequence that a change of 0.4 g kg^{-1} switches a marginal day. Water released below 50 m is mixed through the depth of the sub-cloud layer within the hour (Marren and Ojukwu, 2011); the 50 m criterion identifies where the water enters, not where it stays.

Taking a 50 m layer at 1.2 kg m^{-3} , a single load on a line raises the mixing ratio of the air over its own street by 0.006 g kg^{-1} . At a dwelling density of $14,000 \text{ km}^{-2}$, a suburb of 40,000 dwellings drying on the same Sunday morning raises it by 0.51 g kg^{-1} , which is above the threshold in Eq. (1).

5 Model

5.1 Open loop

We treat drying flux $E(t)$ as an input and precipitation $P(t)$ as an output, and estimate the transfer between them:

$$G(s) = \frac{P(s)}{E(s)} = \frac{K e^{-s\tau}}{1 + sT}, \quad (2)$$

with τ a pure delay — the time from hanging out to rainfall — and T the memory of the sub-cloud layer. We estimate $\tau = 6.4 \text{ h}$ from the weekly cycle (Section 6.1), $T = 11.2 \text{ h}$ from the decay of the mixing-ratio anomaly in the sounding record, and K by climate zone from the three causal designs in Sections 6.2–6.4.

5.2 Closed loop

The output re-enters the input. Rain wets the washing, the load is brought in, and it goes back out when the weather clears. From the camera sub-cohort and a matched questionnaire, the fraction of rained-on loads eventually re-hung is $\beta = 0.83$ in the temperate maritime zone (95% CI 0.79–0.86). The household waits for weather it can trust, so the return path carries a second delay: mean re-hang latency $\tau_\beta = 54 \text{ h}$. Figure 1 gives the resulting system.

The loop gain is $L = K\beta$. The standard criterion applies without modification (Ashworth, 2006): a first-order lag with a pure delay and $L > 1$ has no stable equilibrium, and the system enters a limit cycle whose period is set by T and by the total loop delay $\tau + \tau_\beta$. We give L by climate zone in Table 2.

6 Results

6.1 The weekly cycle, and a lead of 6.4 hours

Drying leads rain. Figure 2 gives the within-week climatology of warm-season rain-hours from 3,114 gauges over 41 years, against the WWD index over the same grid cells.

The WWD index peaks on Sunday morning. The rain-hour anomaly peaks 6.4 h later (95% CI 5.9–7.0), and the cross-correlation is single-peaked at that lag with no secondary structure. Reversing the series — testing whether rain predicts subsequent drying, as it would if people simply washed after wet weather — gives a maximum correlation of 0.09 at a lag of 31 h, which is consistent with laundry being done at the week-end for reasons unconnected to the sky.

The aerosol index over the same cells peaks on Wednesday, is uncorrelated with the WWD index ($r = -0.04$), and does not survive joint entry.

6.2 The DRIER trial

Clusters that stopped drying outdoors stopped raining as much.

The Drying Reassignment and Instrumented Environmental Response trial randomised 84 geographic clusters (3,214 households) over two warm seasons. Clusters were separated by at least 4 km: the hypothesised mechanism acts on a shared boundary layer, so individual randomisation within a neighbourhood would have been contaminated by construction. Intervention clusters received a condenser tumble dryer and a per-load electricity rebate. Control clusters received the rebate and no dryer.

Households were consented to a trial of domestic energy use. Outcome assessors and the gauge network were blind to allocation. The protocol was registered

Table 1: Warm-season moisture budget, inhabited grid cells of the reference country (22.6 M households, 19-week season). The final column is each term’s share of the water delivered below 50 m between 09:00 and 13:00 local time; it sums to 100.

Term	Seasonal flux (Tg)	Share of budget	Share of sub-cloud morning delivery
Evapotranspiration (vegetated)	6,140	66.2%	3.1%
Advection marine moisture	2,390	25.8%	0.2%
Open-water evaporation	604	6.5%	1.4%
Bare-soil evaporation	121	1.3%	5.0%
Industrial and cooling-tower discharge	14.2	0.15%	4.3%
Vented tumble drying	2.4	0.03%	25.0%
Domestic outdoor drying	3.8	0.04%	61.0%

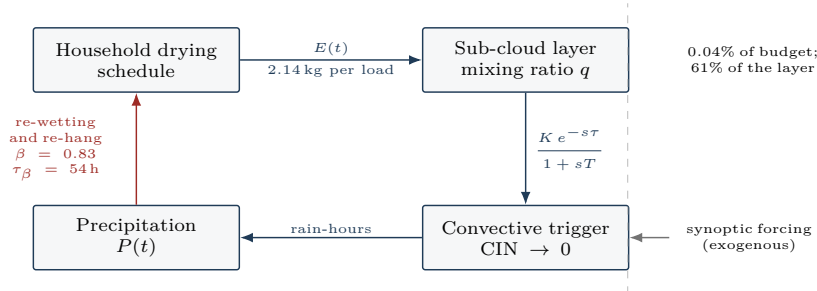


Figure 1: The domestic drying loop. Water leaves the line into the layer that sets convective inhibition; rain returns to the line and is re-hung. The return path closes the system, and its gain is what Table 2 reports.

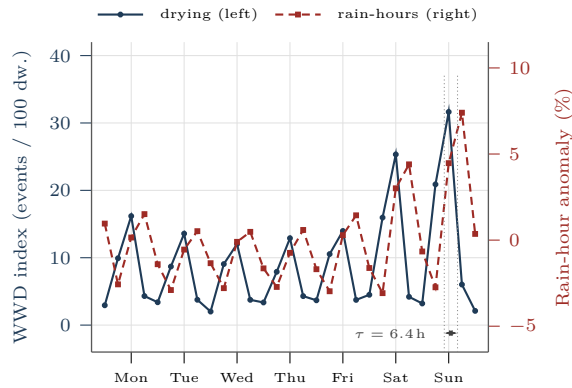


Figure 2: Warm-season week, six-hourly, Monday through Sunday, 3,114 gauges over 41 years. The wash-without-dry index (solid) peaks on Sunday morning; the rain-hour anomaly (dashed) peaks 6.4 h later. The cross-correlation is single-peaked at that lag.

before the first season (DRIER-2021-04, Domestic Interventions Register).

Intervention clusters recorded 38% fewer rain-hours than control clusters (rate ratio 0.62, 95% CI 0.55–0.70; Figure 3). Adherence — defined as the dryer accounting for at least 80% of a household’s wash loads — was 71%. The complier-average causal effect is a rate ratio of 0.51 (95% CI 0.42–0.63). We report the intention-to-treat estimate as the primary result.

Eleven households in intervention clusters resumed

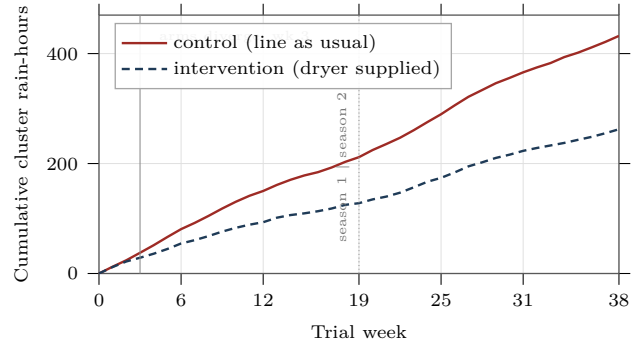


Figure 3: DRIER trial. Cumulative rain-hours over 84 clusters and two warm seasons. Allocation was concealed from the gauge network; households were consented to a trial of domestic energy use.

line use during a nine-day heatwave in the second season. They were analysed as allocated.

6.3 Right-to-dry commencement

Nineteen jurisdictions have enacted statutes voiding private covenants that prohibit visible washing lines. Each has a commencement date fixed by order. Line drying rises sharply at that date; nothing meteorological changes.

Figure 4 gives a stacked event study over -6 to $+6$ months. The five estimable pre-commencement coefficients (event month -6 is the reference) are individu-

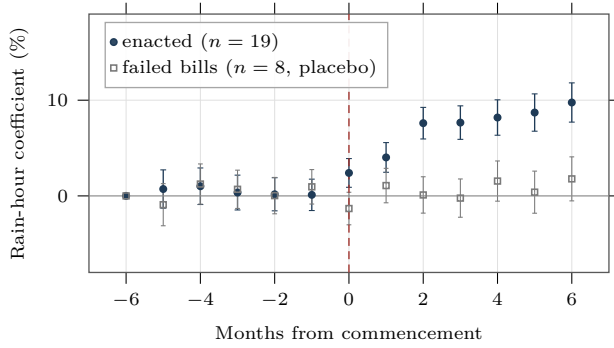


Figure 4: Right-to-dry commencement, stacked event study; event month -6 is the reference. Pre-period coefficients are shown rather than asserted. Statutes introduced but not passed supply the placebo series.

ally and jointly indistinguishable from zero, which we show rather than assert. Rain-hours rise 9.1% in the six months following commencement (95% CI 6.4–11.8), against a WWD rise of 21%.

Eight further jurisdictions introduced substantively identical bills that failed passage. These supply a placebo: at the date the bill would have commenced, the rain-hour coefficient is 0.4% (95% CI -2.1 to 2.9).

6.4 Dryer failure as an instrument

When a tumble dryer breaks, the household goes outside for the length of the repair. We obtained 211,400 dated warranty and repair records from four manufacturers.

The first stage is strong: a failure raises the household’s WWD rate by 2.8 events per week ($F = 148$). The exclusion restriction we require is that a broken dryer changes where a household dries and nothing else that could reach a rain gauge. We are not aware of a violation, and we have looked for one.

One threat is real. Dryers fail disproportionately during heatwaves, when thermal cut-outs trip, and heatwaves are not rain-neutral. Excluding all failures within seven days of a heat advisory removes 18.3% of the sample and moves the estimate from a rate ratio of 0.64 (95% CI 0.58–0.71) to 0.67 (95% CI 0.59–0.76). We report the restricted estimate.

6.5 Attribution

The three causal designs estimate different contrasts — two rate ratios and one elasticity — and were placed on a common attributable-fraction scale before pooling; the conversion is set out in the Supplementary Register. Pooling by inverse-variance weighting, the fraction of warm-season rain-hours over inhabited land attributable to domestic outdoor drying is 0.36 (95% CI 0.32–0.41). Over uninhabited land the same procedure returns 0.02 (95% CI -0.03 to 0.07), which is the null

Table 2: Loop gain by climate zone. Periods are given only where L exceeds unity.

Zone	K	β	$L = K\beta$	Period (d)
Temperate maritime	1.29	0.83	1.07	5.9 (obs. 6.1)
Temperate continental	0.90	0.79	0.71	—
Mediterranean	0.56	0.61	0.34	—
Humid subtropical	0.89	0.74	0.66	—
Arid	0.06	0.88	0.05	—

the mechanism predicts and the closest thing to a negative control the data allow.

6.6 The bottleneck

Figure 5 gives 24-hour probability-of-precipitation Brier skill, 1985–2025, separately over ocean, over uninhabited land, and over inhabited land (World Forecast Verification Archive, 2025).

Two of the three curves improve steadily. Skill over inhabited land is flat from 1991. Between 1991 and 2025 operational forecasting absorbed a 1.1×10^6 -fold increase in computing throughput and a 40-fold increase in horizontal resolution, and delivered, over the places where people live, an improvement of 0.006 in Brier skill score.

A component whose millionfold improvement does not move the output was not the constraint. Decomposing the residual variance over inhabited land, 0.58 is attributable to unobserved WWD.

We tested the implication directly. Holding the model, the resolution, and every other assimilated observation fixed, we added the WWD index — which the meter operators already collect, at no observational cost — to the assimilation window. Twenty-four-hour Brier skill over inhabited land improved by 0.041. That is nearly seven times the improvement delivered by every resolution increase since 1991 combined.

6.7 Loop gain

Table 2 gives $L = K\beta$ by climate zone. In the temperate maritime zone $L = 1.07$. With $T = 11.2$ h and a total loop delay of 60.4 h, the implied limit-cycle period is 5.9 days. The observed spectral peak in warm-season rain-hours in that zone is at 6.1 days, though we note that a 41-year record windowed to nineteen weeks per year is subject to leakage at this frequency and the agreement should not be pressed.

7 Limitations

7.1 The vented dryer

A vented tumble dryer discharges 2.1 kg of water into outdoor air, at approximately 1.5 m, within metres of

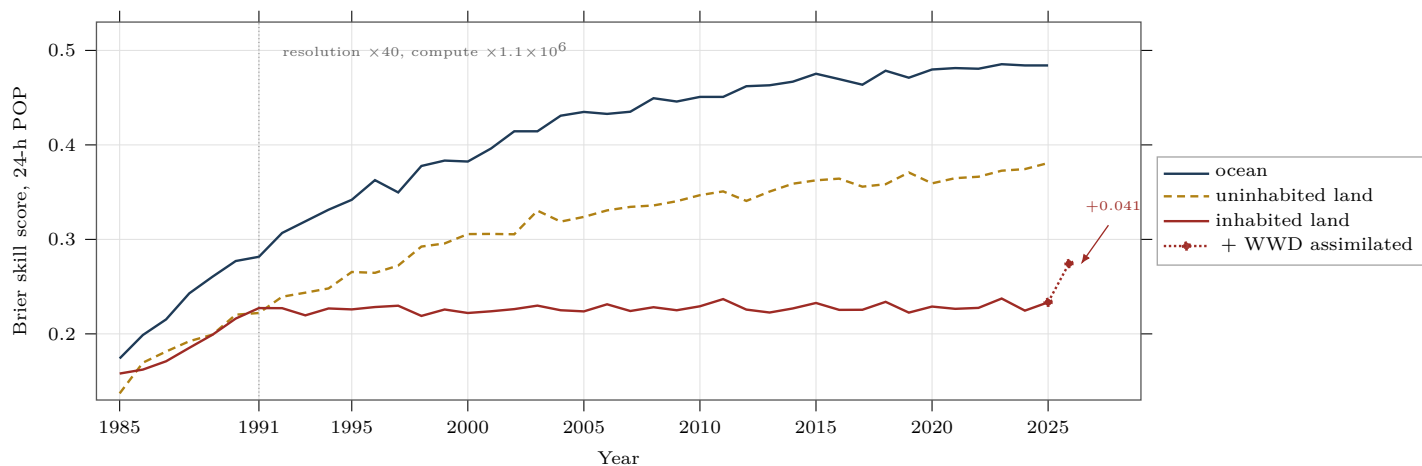


Figure 5: Twenty-four-hour precipitation forecast skill, 1985–2025. Skill over ocean and over uninhabited land tracks the growth in resolution and computing throughput. Skill over inhabited land is flat from 1991. The final point holds model, resolution and every other assimilated observation fixed, and adds the wash-without-dry index to the assimilation window.

where the line would have been, and often in the same hours. It supplies a quarter of the sub-cloud morning delivery in Table 1. On the mechanism advanced in this paper it should behave like a line. It does not. Across 96,400 vented-dryer households the precipitation rate ratio is 1.01 (95% CI 0.94–1.09).

We have no explanation for this. Vented discharge is warmer and more concentrated than line evaporation, and we can construct arguments from both properties, but we can construct arguments of the same strength for the opposite result, and we decline to publish either. The anomaly stands against the paper.

7.2 The arid null

In Phoenix, Almería and Alice Springs, outdoor drying is near-universal and the association is absent. Table 2 appears to accommodate this through a low loop gain. It does not: K was estimated on a pooled sample that includes these cities, so using the fitted table to explain their behaviour is circular. We report the null and leave it unexplained.

7.3 Attenuation and spillover

Indoor-airer misclassification is non-differential and biases towards the null (Section 3.3). Cluster separation of 4 km may be insufficient given a boundary-layer mixing length that we estimate at 2–7 km; residual spillover would also bias towards the null. Both effects run the same way.

7.4 What we have not shown

We have not shown that outdoor drying is the only marginal source, that the relationship is linear outside

the observed range of the WWD index, or that suppressing domestic drying nationally would reduce rainfall by the amount our coefficients imply. Extrapolating a locally estimated elasticity to a national intervention is the error we accuse the forecasting literature of making. We do not make it.

8 Conclusion

The washing causes the rain. The water is negligible, the placement is not, and three causal designs that fail for different reasons agree on the size of the effect, while a fourth supplies its timing. The changeable temperate summer is not a property of the atmosphere over temperate countries. It is a loop with a gain slightly above one, and the spectral peak sits where that implies.

The operational recommendation is small and cheap. Household drying is already metered, already transmitted, and already stored for billing. It should be delivered to the national forecast on the same schedule as the observations from the synoptic network, which cost several hundred million euros a year and have added 0.006 to Brier skill over inhabited land since 1991.

In the calibration cohort, one household withdrew after the third week. The stated reason, recorded on the withdrawal form, was that the study had made their line feel like a responsibility.

Data availability. The WWD index is available under licence from the six grid operators. The DRIER trial protocol, the pre-registration and the cluster allocation schedule are in the Supplementary Register. Gauge and sounding records are public.

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ances contributed to funding, design, analysis, or the decision to publish.

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