



Brief communication: GNSS water-vapour fluctuations read the air mass of the 2024 Rio Grande do Sul and 2022 Recife floods hours ahead of the heaviest rain

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Abstract. Satellite-positioning antennas measure the water vapour above them, and the minute-to-minute fluctuations of that measurement, usually smoothed away, describe how the moisture is arranged. We read them at eleven Brazilian antennas during two floods with little or no radar coverage, in Rio Grande do Sul in 2024 and at Recife in 2022, against six-hourly rain gauges. Over a season they separate wet from dry periods 6 to 12 hours ahead, with an area under the receiver operating characteristic curve of 0.80 to 0.87. In both floods the antennas rose into their top 5 % hours before the worst rain.

1 Introduction

Two of the deadliest rainfall disasters of the past decade in South America were convective episodes over areas that no weather radar covered adequately. In Rio Grande do Sul, a cold front held in place by a blocking anticyclone produced a state-wide average of 304 mm between 27 April and 6 May 2024 (Simoes-Sousa et al., 2025), three months of rain in two weeks (Clarke et al., 2026), and the highest flood on record in Porto Alegre. In Recife, a succession of easterly waves and a cold front produced 551 mm between 25 and 30 May 2022, most of it on 25 and 28 May, and more than 130 people died in landslides along the coast of Northeast Brazil (Marengo et al., 2023; Koseki et al., 2025). In both cases warnings were in force; at Recife they underestimated the rain to come (Marengo et al., 2023). Such underestimation is the usual weakness of the warning chain at the range of hours: convective rainfall is the part of the forecast that degrades fastest with lead time, and the gap is normally filled by nowcasting, which extrapolates radar echoes once rain has formed (Sun et al., 2014). Here that gap stayed open. The flooded area of Rio Grande do Sul had no radar until one was installed in August 2024 (Defesa Civil do Rio Grande do Sul, 2026), and the only radar serving Recife stands 82 km inland. What both regions did have were permanent antennas of the Brazilian Network for Continuous Monitoring of GNSS (RBMC), installed for surveying, which measure the water vapour above them every 30 s. What those measurements showed during the two floods is the subject of this communication.

A GNSS antenna receives signals from navigation satellites, and the water vapour along the path delays them by a small, measurable amount. Expressed as an equivalent extra path length, this quantity is the zenith wet delay: it is proportional to the total water vapour above the antenna and available every 30 s in all weather (Bevis et al., 1992; Guerova et al., 2016). Meteorology has used it for three decades as an amount, smoothed in time, to constrain forecast models or to map the moisture field (Boniface et al., 2009). The smoothing removes the way the delay varies from one minute to the next. These variations are



the moist and dry patches of the lower atmosphere passing through the field of view of the antenna (Kermarrec et al., 2025), and two parameters describe them over each hour (Lilly et al., 2017; Kermarrec et al., 2025). The first, σ , is the amplitude of the variations, in millimetres of delay: how much water vapour is being stirred. The second, λ , is the rate at which the pattern renews itself, in inverse seconds: a small value means that large, long-lived structures are passing, a large value that they are small and short-lived. When the air organises itself into larger and more vigorous moist structures, as it does before convection, λ decreases while σ increases. GNSS water vapour has been linked to deep convection before, through convergence time scales in the Amazon (Adams et al., 2013), maps of the amount over Europe (Brenot et al., 2013) and assimilation into convective-scale models (Zheng et al., 2025); all of these use the amount, over a network or in a model. The amount says how much water stands above the antenna; σ and λ say how it is distributed in time as it drifts past. That second piece of information keeps varying even when the column is saturated and the amount can no longer rise.

This communication reads these two parameters, together with the amount of vapour, at the antennas of the two regions where radar could not fill the gap, over a whole season and during the floods, and judges them against rain gauges. The range is that of nowcasting: an observation of the present state of the atmosphere, updated every half hour, with a useful lead of a few hours, complementary to the forecasts on which warnings are built. Assimilating the delay into a convective-scale model is the other way to use these antennas, and the more powerful one where such a model runs over the region; an index is read directly, without a model and without an assimilation cycle, which is what makes it usable where neither is available.

2 Data and methods

2.1 Antennas and rain gauges

Six antennas span Rio Grande do Sul (POAL, RSSL, RSPE, RSPF, SMAR and SCLA, 30 to 270 km apart) and five the coast of Northeast Brazil (PERC, PBJP, PBCG, RNNA and ALAR); Fig. 1 shows their positions with the rain gauges used as truth and the rainfall each gauge recorded during the flood windows. Their zenith wet delays were computed every 30 s by precise point positioning with ambiguity resolution (PRIDE PPP-AR; Geng et al., 2019), over 1 March to 15 May 2024 and 1 April to 10 June 2022, using a single family of satellite orbit and clock products for each antenna. Rainfall truth is taken from a source independent of any forecast: the 6-hourly totals reported by synoptic stations and archived in the Integrated Surface Database (ISD) of the United States National Oceanic and Atmospheric Administration (NOAA; Smith et al., 2011). For each antenna the nearest station is used, 6 km from POAL (Porto Alegre airport) and 9 km from PERC (Recife airport), completed by the hourly automatic stations of the Taquari valley summed over 6 h. A 6-h period is classed as wet above 10 mm, extreme above 30 mm and dry below 0.1 mm. The two flood windows, 26 April to 5 May 2024 and 23 May to 1 June 2022, are excluded from every calibration. All times are given in Coordinated Universal Time (UTC).

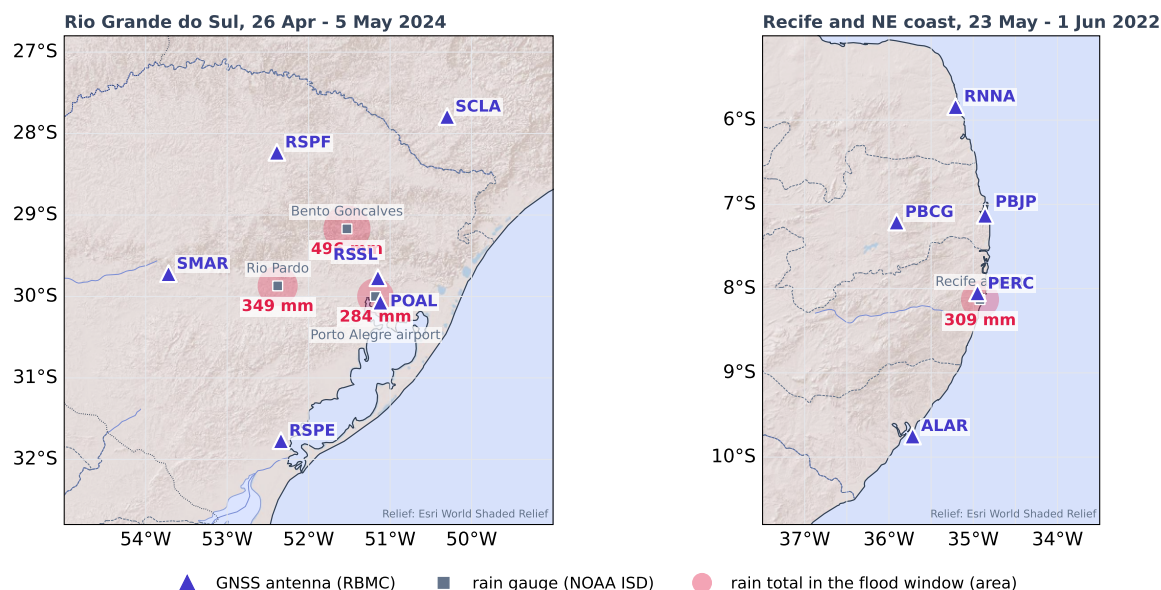


Figure 1. The two RBMC antenna clusters (indigo triangles), the synoptic stations used as rainfall truth (slate squares), and the rainfall recorded by each station during the flood window (circle area proportional to the total). Left: Rio Grande do Sul, 26 April to 5 May 2024. Right: Recife and the coast of Northeast Brazil, 23 May to 1 June 2022. The João Pessoa station is omitted because its 6-h record is too sparse.

2.2 Three indices from the same record

From the 30 s wet delay, σ and λ are estimated in sliding windows of 62.5 min by fitting the spectrum of the fluctuations with a Matérn model (Lilly et al., 2017; Sykulski et al., 2019), which yields one value of each parameter per antenna and per window. Each value is then turned into a dimensionless number, its departure from that antenna's median divided by that antenna's interquartile range, so that σ and λ are both counted in units of their own habitual variability. Each antenna is thereby compared with its own past rather than with its neighbours, which is what makes a network of different receivers readable at all, and the two dimensionless numbers can be combined. Three indices were declared before any test. Texture is the dimensionless σ minus the dimensionless λ : it is high when the fluctuations are at once unusually large and unusually slow, that is when the air is organising. Vapour is the departure of the wet delay from the antenna's climatology for that hour of the day, in the same units. The third index is their sum, which responds when the column both moistens and becomes more agitated, as it does when a moist air mass arrives and starts to organise.

2.3 Skill and lead time

For each 6-h period, the feature is the mean of an index over the preceding 6 to 36 h, ending 30 min before the period so that nothing measured during the rain enters the value. Skill over the season is the area under the receiver operating characteristic



curve (AUC): the probability that a randomly chosen wet period has a larger feature than a randomly chosen dry one, 0.5 for no skill and 1 for perfect separation. Its 90 % interval is obtained by resampling whole days. The index applied to the floods is selected by leave-one-week-out cross-validation: for each week of the season, the index with the highest AUC on the other weeks is applied to that week, so that the choice never depends on the answer. The cluster state is the median of the antennas at each period. During the floods, the state is reported as a percentile of the same antenna's dry-weather values of the season; a value of 95 means that only 5 % of the dry periods of that season had a larger feature. Four predictions concerning the season skill, the cost of cross-validation, the state at the first extreme period of each flood and the onset of rain episodes were written and dated before the computations. The register, including the predictions that the data refuted, is deposited with the code (Kermarrec, 2026). No threshold is used except in Sect. 3.3, where one alert rule declared in advance is evaluated.

3 Results

3.1 Skill over the season

Table 1 gives the AUC of the 12-h feature. At a single antenna, vapour separates wet from dry periods with an AUC of 0.80 [0.73–0.88] in Rio Grande do Sul and 0.81 [0.73–0.89] at Recife; the sum reaches 0.74 and 0.80, the texture 0.67 [0.60–0.73] and 0.69. The median of the antennas raises the vapour AUC to 0.87 in both regions, as expected when receivers whose errors are independent are averaged. Cross-validation selects vapour in every week in Rio Grande do Sul and in six weeks out of seven at Recife. The index selected this way reaches an AUC of 0.77 and 0.76 at the antenna and 0.84 and 0.82 at the cluster, within 0.05 of the best fixed index. Onsets, defined as wet periods with no rain above 10 mm in the previous 48 h, are anticipated slightly better than the periods that follow them. Vapour reaches an AUC of 0.87 and 0.85 six hours ahead of an onset, against 0.77 and 0.76 later in an episode, and falls at longer leads, to 0.77 at 36 h. Texture reaches 0.72 and 0.79 ahead of onsets. The three indices are not independent, since they share the same wet delay, and their sum does not exceed the better of the two in either region. What texture adds is therefore not extra skill on this kind of truth, but its behaviour where vapour saturates, illustrated by the Recife episode below. A single lead time of 6 to 12 h therefore applies to the first rain of an episode and to its peaks. Among wet periods, none of the three indices separates totals above 30 mm from totals between 10 and 30 mm, the AUC ranging from 0.38 to 0.60 with intervals that include 0.5. The skill reported above therefore concerns the occurrence of heavy rain in the next 6 to 12 hours and not its amount, which is what a measurement integrated over the whole column can be expected to carry.

3.2 The two floods

Figure 2 follows the cluster through both episodes, as a percentile of its dry-season values, together with the gauge rainfall and the official warnings. In Rio Grande do Sul the cluster reached the 94th percentile on 26 April at 12 UTC, the day of the first INMET (Instituto Nacional de Meteorologia) notice (INMET, 2025) and 36 h before the first extreme period, 45 mm at the airport ending on 28 April at 00 UTC. It exceeded the 95th percentile on 29 April at 18 UTC, the day of the first red



Table 1. Skill over the season: AUC of the 12-h feature for wet (≥ 10 mm in 6 h) against dry (< 0.1 mm) periods, flood windows excluded, with 90 % intervals from resampling days. The last two rows give the index selected by leave-one-week-out cross-validation and the AUC obtained with it.

	Single antenna		Cluster median	
	RS 2024	Recife 2022	RS 2024	Recife 2022
Texture (σ minus λ)	0.67 [0.60, 0.73]	0.69 [0.59, 0.77]	0.72 [0.61, 0.82]	0.76 [0.63, 0.87]
Vapour	0.80 [0.73, 0.88]	0.81 [0.73, 0.89]	0.87 [0.81, 0.93]	0.87 [0.78, 0.94]
Sum	0.74 [0.67, 0.80]	0.80 [0.74, 0.86]	0.79 [0.71, 0.86]	0.87 [0.79, 0.93]
Cross-validated choice (weeks)	vapour (6/6)	vapour (6/7)	vapour (6/6)	vapour 3, sum 3
AUC of that choice	0.77	0.76	0.84	0.82
Wet / dry periods	52 / 1040	14 / 298	17 / 156	7 / 148

warning, and remained above it during the three heaviest periods of 30 April, of 39, 70 and 62 mm. At Recife the state alerts came first: CEMADEN (Centro Nacional de Monitoramento e Alertas de Desastres Naturais) issued moderate-level alerts for the metropolitan region on 23 May at 19 UTC and raised the landslide alert to very high the same evening (Marengo et al., 2023). The antenna PERC exceeded its 95th percentile on 24 May at 06 UTC, 11 h after the first alert and on the day of the first heavy rain. It stayed above it through the dry days of 25 and 26 May, fell during the onset of the deluge of 27–28 May, and returned to the 98th–100th percentile until 1 June. A moist air mass sat over the region for a week, and in such a saturated maritime regime vapour has little room left to increase. The prediction that at least half of the antennas would be above their 95th percentile at the first extreme period was verified at Recife (PERC, 98.5th percentile) and refuted in Rio Grande do Sul. There the cluster stood at the 92nd percentile at that period, three points below the line fixed in advance, and Porto Alegre alone between the 64th and 70th. The prediction is counted as missed. The cluster crossed the line 42 h later, on 29 April at 18 UTC, and stayed above it through the three heaviest periods. Over this stalled front the moisture built up gradually, so that the extreme state marked the culmination of the episode rather than its start.

Before extreme periods, the neighbouring antennas exceeded their own 95th percentile seven times more often than in dry weather (30 % against 4 %), whether they lay on the side from which the rain arrived or on the opposite side. The elevated state was therefore regional and simultaneous; at the 50 to 250 km spacing of this network, no propagation could be resolved.

3.3 One alert rule and its cost

One rule was declared before the data were examined: a cluster state above the 95th percentile for two consecutive periods (12 h). It gives one alert in each episode, on 30 April at 00 UTC, 6 to 18 h before the three heaviest periods of Rio Grande do Sul, and on 26 May at 18 UTC, 36 to 42 h before the two heaviest periods of Recife, of 44 and 108 mm. Over the season the same rule is triggered on 16 % of the dry days in Rio Grande do Sul and on 11 % at Recife. Requiring one period (6 h) instead of two gains six hours in Rio Grande do Sul at the cost of 1.6 additional points of false alarms, and doubles the cost at Recife

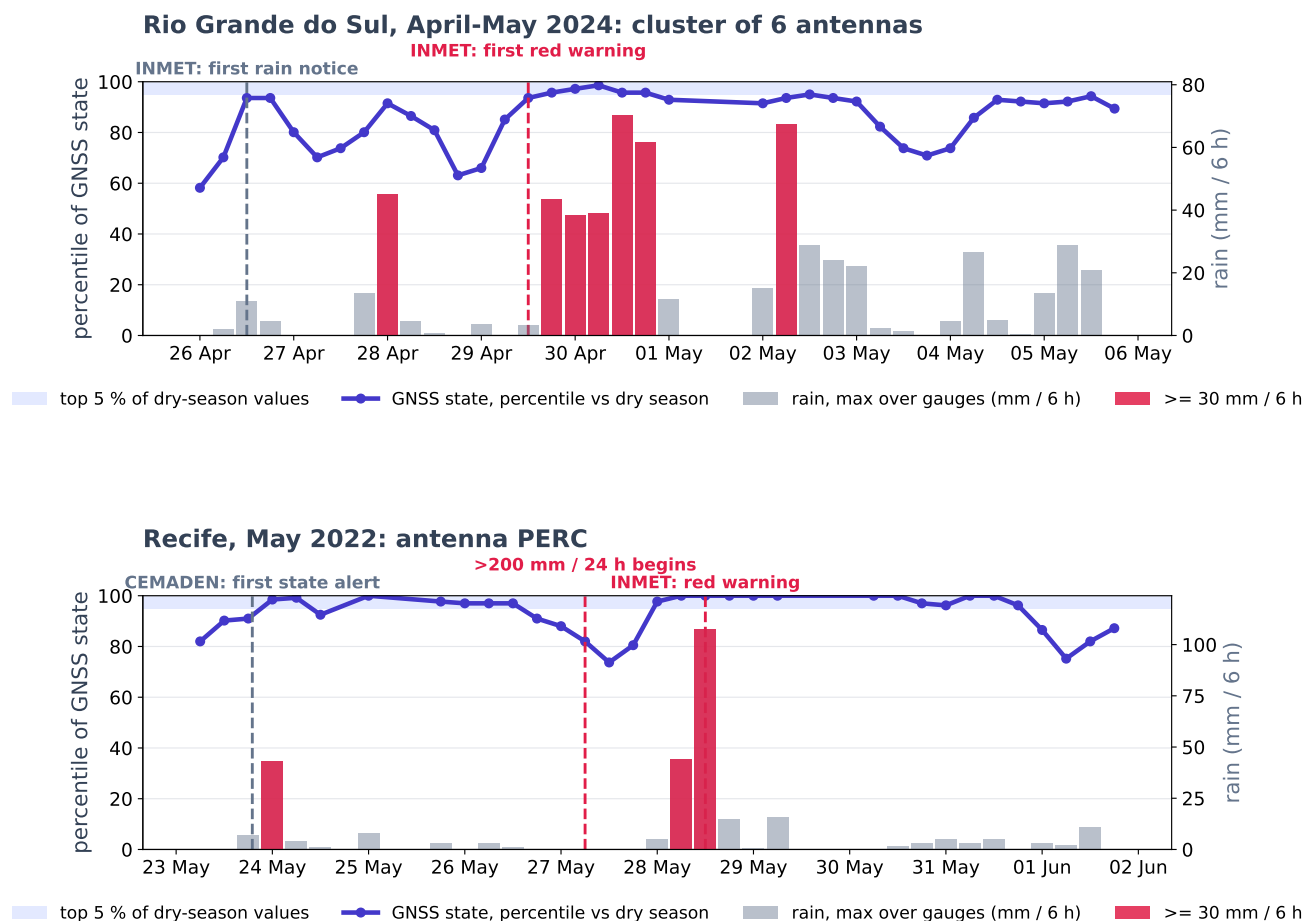


Figure 2. State of the antennas during the two floods. Line: cluster median of six antennas (Rio Grande do Sul) or antenna PERC (Recife), expressed as a percentile of the dry-weather values of the season for the index selected by cross-validation (vapour); the shaded band marks the top 5 %. Bars: 6-h rainfall at the gauges, in red above 30 mm. Dashed lines: official notices, alerts and warnings (INMET, Civil Defence, CEMADEN) and, at Recife, the onset of the 24-h deluge.

120 (25 %), where the saturated state repeatedly crosses the threshold. In both episodes the alert comes after the first extreme period and before the heaviest ones, at the onset of which the cluster stood at the 92nd and 94th percentiles, just below a line fixed in advance at 95. Set against the official warnings, which are forecast-based and issued days ahead, the alert falls on the night after the first INMET red warning in Rio Grande do Sul, and three days after the first CEMADEN alert at Recife, where the air mass had been in place since 23 May. The two products therefore do not compete: the warnings say that a dangerous situation
125 is expected, the antennas say how the air above the region stands at that moment.



4 Conclusions

The skill of these indices rests on two bodies of evidence of unequal weight. A season of 52 wet and 1040 dry periods in Rio Grande do Sul, and of 14 and 298 at Recife, supports interval estimates; two flood episodes illustrate how the indices behaved, and measure nothing. The fluctuations and the amount of water vapour recorded by existing surveying antennas show the same short lead time in both regions and both regimes, 6 to 12 h, for the onset of an episode as for its later peaks. Vapour is the most skilful index (AUC 0.80 and 0.81 at a single antenna) and texture follows close behind (0.67 and 0.69, and 0.72 and 0.79 ahead of onsets). The two are not interchangeable. The amount of vapour says how much water stands above the antenna; λ and σ say how that water is arranged, and they rise together when the moist field coarsens and becomes more agitated, which is what an atmosphere does as it organises for convection. The Recife episode shows the difference: in a saturated maritime regime vapour has little room left to increase and stays at the top of its range for a week, while the texture keeps varying. Where the column is already near saturation, the arrangement of the moisture is the only part of the signal left to read. During the two disasters the antennas were in the top 5 % of their season before the heaviest rain, by 18 h in the frontal situation of the south and by 36 to 42 h in the saturated maritime situation of the northeast. Two episodes cannot establish a lead time, and one of the four sealed predictions was refuted; the cases show how an observable of measured season skill behaved, not what it would achieve. In the latter case the state persisted for a week and indicated the presence of the dangerous air mass rather than the timing of its storms. The state was also regional: an antenna 30 km from the rain recorded it as well as its neighbours, and combining antennas improves the precision of the median without adding a direction. The indices give no information on the amount of rain, and its lead time does not extend beyond 12 h: this is a nowcasting observable, complementary to forecasts issued days ahead, and it is judged here as such. The alert rule evaluated here produces one alert per episode for one false-alarm day in six to nine, and every number above can be recomputed from the deposited parameters and checked against registers dated before the results were known.

A comparison with radar was possible in neither region. No radar covered the flooded area of Rio Grande do Sul in April 2024. The Chã Grande radar, in service since 2016, stands at 470 m altitude at the distance given above. Over the metropolitan region its lowest beam therefore samples the atmosphere more than a kilometre up, and misses the layer where the sea breeze prepares coastal convection. Its products are published as images and accumulations, and a quantitative comparison would require a data request to the state agency. Where radar volumes are archived, the same parameters have been verified against echoes, and the two observations are complementary: radar measures rain once formed, whereas λ , σ and the departure of the wet delay from climatology describe the vapour field hours before any echo exists.

What this opens is concrete. The RBMC alone has 153 active antennas across Brazil (IBGE, 2025), and thousands of comparable antennas exist worldwide, many of them in regions that will never have radar coverage. Their wet delays are already computed for positioning; the parameters used here follow from them at the cost of a spectral fit per hour. The test that follows is therefore within reach: one rainy season of one such network, run in real time, with the rule declared here and its alerts logged before the rain falls. Should it hold, regions that will wait years for a radar would gain, at no new hardware cost, a measurement of the air above them updated every half hour.



160 *Code and data availability.* The fluctuation parameters λ and σ of the eleven antennas, the 30 s wet delays, the season and event tables, the sealed-prediction registers with their dates of freezing, the outputs reported here and the analysis code from the parameters onward are deposited at <https://doi.org/10.25835/v40ouls8> (Kermarrec, 2026). RINEX observations are distributed by IBGE (RBMC), rainfall by NOAA ISD (Smith et al., 2011), warnings by INMET (INMET, 2025) and CEMADEN (Marengo et al., 2023).

Author contributions. GK designed the study, processed the data and wrote the manuscript.

165 *Competing interests.* The author declares no competing interests.

Acknowledgements. The author used a large language model (Claude, Anthropic) to assist with drafting and editing the manuscript and with writing the analysis scripts; the study design, the analyses, the results and the conclusions are the author's own and were verified against the code and registers deposited with this paper. This work was supported by the Deutsche Forschungsgemeinschaft (DFG) through project LES2GNSS (KE 2453/4-1, project no. 547859686). Computations were carried out on the LUIS cluster of Leibniz Universität Hannover.

170 The author thanks IBGE for the open RBMC archive, NOAA NCEI for the Integrated Surface Database, INMET and CEMADEN for the public record of their warnings, and the developers of PRIDE PPP-AR for their software.



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