

Differentiating wind risk: Discussion paper

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Executive Summary

Over the past decade, over sixty percent of Ausgrid's outage minutes were caused by weather related events, and of these ninety-eight percent were caused by windstorms. Understanding wind related risks is therefore an important part of Ausgrid's climate resilience planning.

In recent regulatory decisions concerning wind resilience investments, the Australian Energy Regulator (AER) has commented that Distribution Network Service Providers (DNSPs) "assume segments on the feeder are being treated as being equally at risk to increasing climate hazards, whereas in practice some segments are more vulnerable than others." (AER, 2026). The AER's statement encourages us to provide better value for customers by improving modelling of comparative wind risk along the feeder, so that segments with higher wind risk can be targeted.

This paper opens a discussion on how DNSPs could draw on practices from adjacent industries to better model wind risk and target resilience investment. Ausgrid's climate change model currently uses the NARClIM2.0 dataset at 4km resolution, bias corrected with BARRA-C2 historical reanalysis data. This grid spacing is too coarse to resolve many of the terrain effects that matter to distribution-network assets: ridge acceleration, valley sheltering, lee effects, exposure to prevailing wind directions, and sharp local gradients.

This paper considers whether other established wind-risk practices could help Ausgrid better direct investment, compared to using climate-change datasets alone. Terrain Dynamic Models, which are backed by academic literature, have been used widely in the wind generation industry for over 20 years, and in bushfire modelling services for over 15 years. Terrain models use dynamic modelling to calculate how hills, valleys, ridgelines, escarpments and vegetation alter wind speed to identify locations with weaker or stronger comparative risk.

Table 1 Model terminology used in this report

Model	Primary purpose	Examples	Uses
Terrain Dynamic Models	Simulates how wind interacts with the landscape to identify areas with elevated risk, predominantly in the current environment.	WindNinja, WindLab	Phoenix RapidFire tool Wind Generation Industry
Climate Change Projections	Produce insights about how wind might change at a 4km resolution under different emission scenarios.	NARClIM2.0	In climate change risk assessments

There is a growing industry practice of integrating climate data sets with terrain modelling for improving risk assessments. For example, 'the University of Melbourne's PHOENIX-based fire risk modelling applies a WindNinja-derived terrain wind layer to BARRA gridded weather, then adjusts the resulting risk for future weather patterns using NARClIM projections' (Cirulis, 2026).

We propose a similar, practical method to understand wind risk using both climate change data sets and terrain models. This method uses NARClIM2.0 climate projections, bias-corrected using BARRA-C2 historical reanalysis data, to estimate changes in wind intensity and frequency, and applies terrain-derived insights from WindNinja (the same terrain model used in PHOENIX) to identify locations where wind risk is likely to be elevated within the climate model grid. By bringing these insights together we can identify segments of a feeder with lower or higher comparative risk¹.

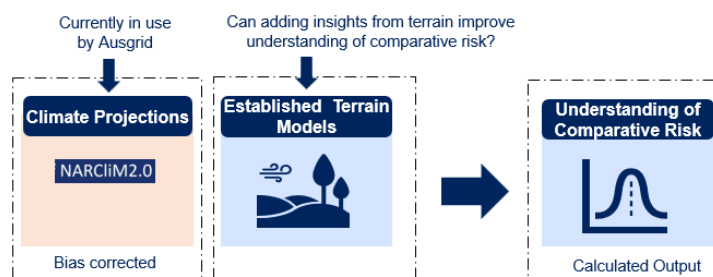


Figure 1 Explanation of the proposed approach

¹ The proposed method does not seek to resolve accuracy, precision, or certainty of the underlying climate projections, nor is it an attempt to 'downscale' NARClIM2.0 datasets further. We understand that this requires resolving phenomena like convective downbursts, microbursts and gust fronts that tend to be highly localised. It is a complex process that is not practical for DNSPs to undertake.

Using Terrain-Driven models can help translate the broader NARClIM2.0 climate signals into a more localised view, practically differentiating risk along a feeder. Ausgrid recommends that integrating insights from climate projections and terrain models can be a meaningful and cost-effective step for DNSPs to respond to the AER's request to better identify and target sections of feeders at higher relative risk to create better value for customers.

Whilst this paper focuses on improving the understanding of wind risk by adding terrain modelling to the suite of tools used to assess wind risk, it is relevant to mention that it is not the only way Ausgrid is improving our wind modelling. Other data sets, such as vegetation, historical failures and asset condition can also help indicate locations of higher or lower comparative risk. However, these are excluded from the scope of this paper so that the discussion can focus on the inclusion of terrain modelling.

Requesting feedback:

Ausgrid is inviting feedback from the resilience, scientific and industry communities on our proposed wind methodology.

In particular, we request that you provide response on three questions:

- Generally speaking, not related to Ausgrid's proposed method or the wind peril, do you agree with the principle that risk managers can improve their understanding of climate related risk by using insights from climate models and other information sources such as terrain models, compared to using climate models alone?
- For the purpose of understanding comparative wind risk along a feeder, what are your insights about integrating Terrain Model and Climate Change Projections using the methods laid out in the paper, compared to using Climate Projections alone?
- Given your field of expertise, can you outline any alternative approaches to understanding of comparative wind risk along a feeder?

1. Introduction

Over the past decade, over sixty percent of Ausgrid's outage minutes were caused by weather related events, and of these ninety-eight percent were caused by windstorms. Windstorms in Ausgrid's network have resulted in between 100-500k customers being without electricity, in some cases for up to 10-12 days, and led to downstream impacts on other critical infrastructure. Understanding how wind risk may change under future climate conditions is therefore an important part of Ausgrid's climate resilience planning.

Ausgrid currently uses climate change projections, combined with engineering failure curves, to estimate potential asset failure under future wind conditions. We are fortunate to have access to high-quality regional datasets such as BARRA-C2 and NARCIIM2.0. However, for the Ausgrid operating area, these datasets have a grid spacing of approximately 4 km. This is too coarse to resolve the terrain effects that can materially influence distribution-network assets, including ridge acceleration, valley sheltering, lee effects, exposure to prevailing wind directions and sharp local gradients. As a result, applying the same wind speed across a 4 km grid can understate or overstate the differences in exposure between feeder² segments. This aligns with the Australian Energy Regulator's observation that networks can appear to treat "segments on the feeder" as being equally at risk, even though some segments are more vulnerable than others.

More broadly, contemporary climate risk practice increasingly draws on information from multiple domains, rather than relying on climate models alone. This principle is reinforced in the paper *Storylines: A science-based method for assessing and measuring future physical climate-related risks*, where Fiedler et al. highlight the limitations of relying solely on climate models and argue that risk managers should incorporate insights from other domain experts through knowledge co-production (Fiedler, 2024).

For some perils, this multi-pronged approach is already well established. For example, when modelling flooding, climate projections can estimate how rainfall may change across a 4 km × 4 km grid, but they do not describe how water will move through the landscape. Hydrological and hydraulic models are therefore used alongside climate projections to represent the influence of terrain, catchments and infrastructure. Likewise, bushfire risk models incorporate terrain wind layers and adjusts for future weather patterns using climate projections. In these examples, climate data and physical models are both used to produce a more useful understanding of risk.

This paper applies the same logic to wind risk. It reviews wind modelling approaches used in other industries, considers the evidence for their use, and explores whether terrain-based wind models could be integrated with regional climate projections to better differentiate comparative wind exposure across Ausgrid's network.

Whilst this paper focuses on improving the understanding of wind risk by adding terrain modelling to the suite of tools, it is relevant to mention that it is not the only way Ausgrid is improving our modelling. Other data sets, such as vegetation, historical failures and asset condition can also help indicate locations of higher or lower comparative risk. However, these are excluded from the scope of this paper so that the discussion can focus on terrain modelling.

2. Objective

To respond to the Australian Energy Regulator's (AER) comment that Distribution Network Service Providers (DNSPs) "assume segments on the feeder are being treated as being equally at risk to increasing climate hazards, whereas in practice some segments are more vulnerable than others." (AER, 2026), by improving the modelling of *comparative* wind risk along the feeder.

² A feeder is a general term for a circuit that carries power from one part of the network to another, before it gets distributed to customers. It can vary in length from a few kilometres in urban areas to over 50km in rural locations.

3. Background information on the types of wind models in use

To assist the non-technical reader, we introduce the different types of wind models and the features of each. These are summarised in Table 2.

Table 2 Summary of the different types of Wind Models

	Provide insights about how climate might change in the future	Provide information at the asset scale	Accessible to Ausgrid
Terrain Dynamic Wind Models Simulates how wind interacts with the landscape to identify areas with more or less exposure to wind risk.	No, do not consider climate change	Yes, they simulate how wind interacts with the landscape	Yes, some terrain models are freely available
Historical weather reanalysis (BARRA-C2) combines observations with a numerical weather model to reconstruct past weather conditions	No. They reanalyse historical weather.	No, they provide information at a 4km resolution.	Yes, freely available via government portals
Climate Change Projections (NARClIM2.0) Projections about how wind might change due to climate change at a 4km resolution.	Yes, for a range of emissions scenarios	No, provide information at a 4km resolution	Yes, freely available via government portals
Fine-Scale Climate Models Emerging science that resolves small scale phenomena to produce climate change insights at a finer resolution (100m)	Yes, for a range of emissions scenarios	Yes, climate models are downscaled to fine resolution.	No, they are still in development by other parties

Terrain Dynamic Wind Models (Terrain Models)

Terrain models have been used in Australia for over twenty years and simulate how wind interacts with the landscape. Rather than assuming the same wind speed across a region, they calculate how hills, valleys, ridgelines, escarpments and vegetation alter wind speed and direction at a local scale. They were developed independently of climate change studies. More detailed information is in Section 4.

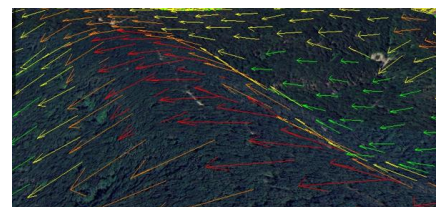


Figure 2 Outputs of a Terrain model

Historical weather reanalysis (e.g. BARRA-C2)

This is a historical weather reconstruction ("reanalysis") that combines observations with a numerical weather model to reconstruct past weather conditions, at a finer scale than many traditional datasets. Unlike climate projections, reanalysis datasets are constrained by real observations and are designed to represent historical weather events. An example is the Bureau of Meteorology's BARRA-C2 dataset, which provides high-resolution historical weather information for Australia at approximately 4.4 km resolution.

Climate Change Projections (e.g. NARClIM2.0)

NARClIM2.0 is a regional climate modelling dataset led by the NSW Government to help organisations understand how climate conditions may change across New South Wales and surrounding regions. The dataset is based on five CMIP6 Global Climate Models (GCMs), which have been dynamically downscaled using two configurations of the Weather Research and Forecasting (WRF) regional climate model, which Ausgrid bias corrects using BARRA-C2. For wind risk assessment, these datasets provide valuable insights into how regional wind speed and frequency may change over time at a 4 km spatial resolution together with information on model uncertainty and confidence. At a resolution of approximately 4 km, it cannot explicitly resolve many small-scale atmospheric processes, such as thunderstorm downbursts, gust fronts and local terrain effects.

Fine Scale Climate Change Wind Models (Fine-Scale Models)

Whilst the NARClIM2.0 regional climate projections downscale to a 4 km resolution, establishing finer-scale climate models has historically been limited by compute capacity. NARClIM2.0 does not fully resolve all wind-generating processes. Convective phenomena such as downbursts, microbursts, gust fronts and embedded storm features can be highly localised, short-lived and intense, meaning peak gusts may be underrepresented or spatially smoothed in climate datasets. Advances in artificial intelligence are enabling climate scientists to develop flexible and adaptive machine learning models that can better predict the probability and impacts of weather-driven phenomena at finer spatial scales. As computing capability and AI methods continue to advance, they may offer new opportunities to improve the representation of localised climate hazards, however building these models is beyond the role and expertise of a DNSP.

4. Evaluation of Terrain Models

Terrain models have been used in Australia for over twenty years. In this section we review established models, select a model for Ausgrid's use and assess the chosen model's efficacy.

4.1 Review of established Terrain Models

To select a model for Ausgrid's use, we compared the following three models against selection criteria (Table 3):

- *WindNinja's Mass-Conserving Model (Simple)* – This computationally efficient configuration adjusts the wind field so that air is redistributed consistently across the terrain, but it uses a simplified representation of the physical forces that shape wind flow. It solves for conservation of mass but not for conservation of momentum.
- *Wind Ninja's Momentum-Conserving Model* – This configuration is more computationally intensive and solves for both conservation of mass and conservation of momentum. It gives a more complete representation of how wind moves around terrain, including the influence of pressure, flow separation and directional effects.
- *WindLab WindScape Raptor Model* – This model was originally developed from CSIRO atmospheric science research and combines mesoscale weather modelling with WindLab's proprietary Raptor microscale flow model. It is designed to simulate the interaction between regional wind patterns and local terrain effects.

Table 3 Summary of Terrain Models against the selection criteria

Criteria	WindNinja Mass-Conserving Model – simple model	WindNinja Momentum Conserving Model (recommended)	WindLab's Windscape/Raptor model
Link to websites	WindNinja US Forest Service Research and Development	WindNinja US Forest Service Research and Development	Windlab
Validated in Academic Literature	Forthofer et al, 2014, validated that it performed reasonably well on windward slopes and crests, but raised that the model is less accurate on the lee-side slopes. See Note 1	Forthofer et al, 2014, validated that it performed well in complex flow regions because it represents momentum and turbulence processes. See Note 1	Yes, was developed from CSIRO atmospheric science. Windlab
Well established use in Australia	This is a simpler model used for quick screening or preliminary assessments	Used in the Phoenix bushfire model and related applications for over 15 years. The Phoenix bushfire application is used by the NSW Rural Fire Service and DNSPs (Parkins, Cirulis, Florec, & Penman, 2020).	Yes, established use in the wind generation industry for over 20 years. (WindLab: What we do, 2026)
Accessibility and Transparency	Yes, available via the website WindNinja US Forest Service Research and Development	Yes, available via Open Source WindNinja US Forest Service Research and Development	This is proprietary software, so not openly available for scrutiny by stakeholders.
Validated by our own modelling	Validation matched the academic literature assessment, with the model performing well on windward slopes but less well on the lee-side.	Results matched the academic literature assessment. More information in available in section 4.3	Was not assessed due to accessibility constraints
Cost	Application is open-source (free). Seconds of compute required per each simulation. (Forthofer, Butler, & Wagenbrenner, 2014)	Application is open-source (free). 30 to 90 minutes of compute required per simulation. (Forthofer, Butler, & Wagenbrenner, 2014)* *2014 processing time	Was not assessed due to accessibility constraints.
Ease of Use	Acceptable for organisations like Ausgrid experienced with handling large datasets.	Acceptable for organisations like Ausgrid experienced with handling large datasets.	Was not assessed due to accessibility constraints.

Note 1 WindNinja's Mass-Conserving and Momentum-Conserving models were evaluated in the journal article A Comparison of Three Approaches for Simulating Fine-Scale Surface Winds in Support of Wildland Fire Management (Forthofer et al., 2014). The authors compared model predictions against measurements from the Askervein Hill and Waterworks Hill field experiments and found that both approaches performed well on windward slopes and hill crests, where terrain effects are most predictable. However, resolving terrain effects on the lee side is more difficult - the study concluded that the Momentum-Conserving model generally provided more accurate results in these complex flow regions because it explicitly represents momentum and turbulence processes, whereas the Mass-Conserving model primarily adjusts the wind field to satisfy continuity constraints.

Ausgrid selected the WindNinja Momentum-Conserving Model because it provides the physical realism, transparency and spatial detail needed to assess wind exposure across the distribution network.

- The model also has an established scientific basis and a history of operational use in Australia
- Being open-source, Ausgrid and external stakeholders can review WindNinja's formulation, assumptions and limitations providing greater transparency than proprietary models.

4.2 Information on the Wind-Ninja Momentum-Conserving Terrain Model

The Wind Ninja Momentum-Conserving Model is a terrain-based wind modelling approach that solves the physical equations governing both the conservation of mass and the conservation of momentum, enabling it to simulate how wind speed and direction change as airflow interacts with complex terrain. Unlike simpler mass-conserving models, which primarily redistribute airflow to ensure continuity, the momentum-conserving model gives it a more complete representation of pressure, turbulence, and directional effects that influence how wind accelerates over exposed ridges, moves through valleys and behaves behind terrain features. In this section we test the academic literature, and research how to practically ingest the model.

Academic validation of Wind-Ninja Momentum-Conserving Model

Forthofer et al. (2014) compared the outputs of the Wind-Ninja Momentum-Conserving model with field measurements. They selected the Askervein Hill (Scotland) and the Waterworks Hill (USA) for comparison as there were field measurements at a spatial resolution relevant to fire management in the complex terrain. The results are shown in Figure 3. The simulated speeds were within 10% of measured values on the windward side, and within 32% of the measured values on the lee side, with the model “under-predicting the speeds at the higher elevation towers”. Forthofer et al. found that “Clearly, such models could be very useful for simulating wind flow in complex terrain in support of wildland fire management”.

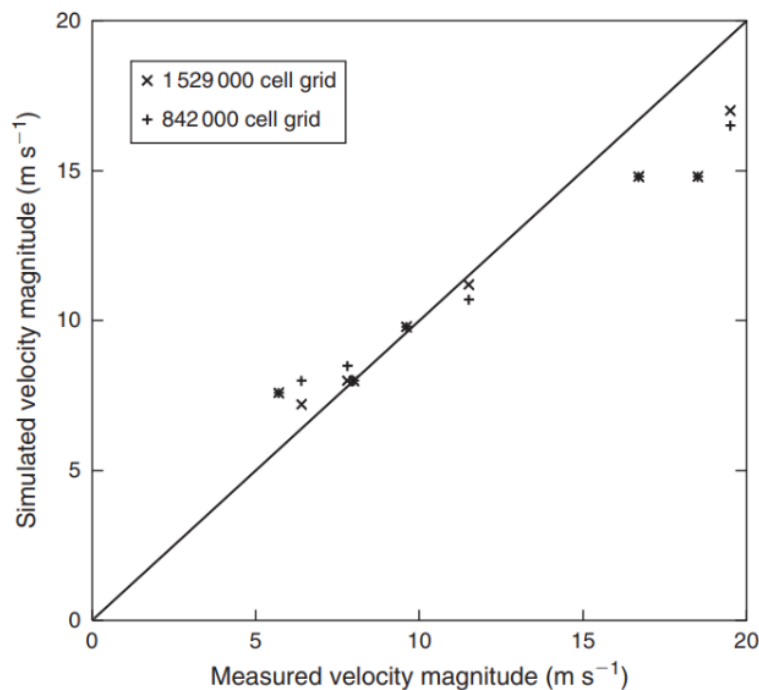


Figure 3: Comparison of measured and simulated wind speed for WindNinja momentum conserving model simulations (Forthofer et al. (2014))

These findings gave Ausgrid confidence that WindNinja warranted further consideration as a potential tool for identifying sections of the feeder at higher or lower comparative risk. A ridge can expose assets on one slope while sheltering assets on the opposite slope. An asset exposed to a north-easterly wind may sit on the sheltered side of the same ridge during a south-westerly wind. Capturing these directional effects allows the model to produce a more credible picture of comparative exposure along a feeder.

Testing the academic research in Ausgrid's operating area

Ausgrid tested how the WindNinja Momentum Conserving Model would function in our operating area. An example is shown in Figure 4 which shows modelled wind behaviour at Mt Sugarloaf. The simulation began with a regional wind speed of 70 km/h across the surrounding grid cell. WindNinja then calculated how the local terrain changed the wind speed and direction. The results show wind accelerating over exposed ridges and slowing in sheltered valleys and lee-side locations. At some ridge-top locations, the simulated wind speed was more than 20 km/h higher

than the regional input. This result makes intuitive sense, as wind speeds vary across a steep landscape, even when the broader regional wind conditions remain the same. Towers on exposed ridge tops can experience much stronger winds than assets in nearby valleys.

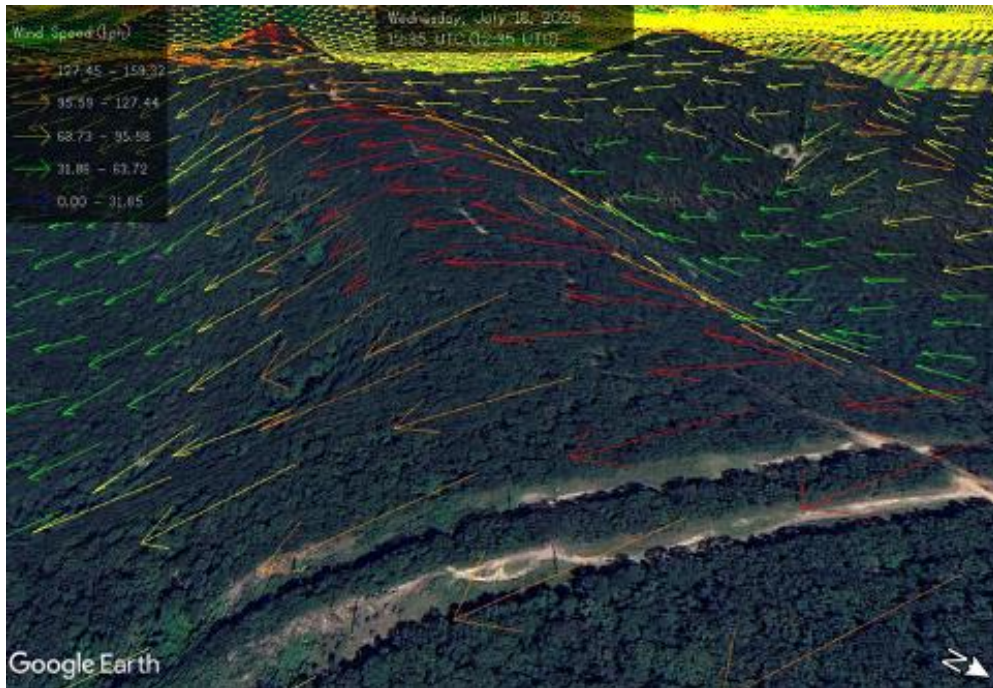


Figure 4 WindNinja simulation of wind speed and direction over Mt Sugarloaf, based on a regional grid wind speed of 70 km/h. Terrain-driven acceleration produces higher wind speeds near exposed ridge tops, while valleys and lee-side locations experience lower wind speeds

Field Testing

Ausgrid is considering further validations of the model using field testing with wind measuring stations, but at this stage has not progressed with field validation. We are still considering how to do this in the most effective way.

5. Modelling methodologies to integrate Climate and Terrain models

In this section we explain how Ausgrid currently ingests climate change data into our statistical model ('Climate model only') and introduce a method to integrate insights from climate and terrain models ('Integrated Approach'). The objective is to determine whether the 'integrated approach' can better identify sections of Ausgrid feeders with relatively higher and lower exposure to wind-related risk compared to the 'Climate Model only' approach.

This study does not aim to:

- Conduct additional atmospheric downscaling of climate model outputs.
- Resolve any uncertainties in the underlying climate projections.
- Predict the timing or magnitude of individual future wind events or wind gusts.
- Undertake economic assessment of mitigation options, which is addressed separately.

The processes explained here are based on the growing industry practice of combining climate change projections with terrain-based models to provide a more comprehensive understanding of future risk. For example, 'the University of Melbourne's PHOENIX-based fire risk modelling applies a WindNinja-derived terrain wind layer to BARRA gridded weather, then adjusts the resulting risk for future weather patterns using NARCLiM projections' (Cirulis, 2026).

Explanation of alternative approaches

Base Case: Use Climate Change Data Only ('Climate model only')

- Input daily maximum wind (sfcWindmax) data from the NSW Government's NARCLiM2.0. The full NARCLiM2.0 ensemble from the SEAus-04 domain consists of 30 simulations (2 x Regional Climate Models x 5 models x 3 scenarios)
- Bias-correct dataset to identify and correct systematic biases in the distribution of NARCLiM2.0 wind data, particularly at the extremes, while retaining the climate-change signal. We use the Quantile Matching for Extremes method for bias correction against BARRA-C2. The BARRA-C2 dataset combines atmospheric modelling with historical weather observations to provide an observation-constrained representation of past winds and gusts.
- Convert sfcWindmax to WindGustMax- We estimate the daily 3 second wind gusts using scaling factors derived from the relationship between hourly winds and the 3 second wind gusts in BARRA-C2.
- We analyse the entire distribution of values across the ensemble to produce a statistical distribution.
- We ingest the processed 4 km NARCLiM2.0 data into engineering models and perform statistical analysis to determine the probability of failure. We use the 'nearest neighbour' approach to identify the 4km grid that the asset falls in and use the same value for all assets with the 4 km grid.

We refer to the outputs of steps (a)-(e) as the '**Processed NARCLiM2.0 Projections**'

Proposal: Uses both Climate Change Data sets and Terrain Models ('Integrated Approach')

- Prepare the Climate Change Data for combining with Terrain Models:**
 - Input the 'Processed NARCLiM2.0 Projections' as per the base case.
 - Divide the NARCLiM2.0 grid into 100m grid cells, giving grid cells wind values and wind direction from the 'Processed NARCLiM2.0 Projections' (Figure 5).

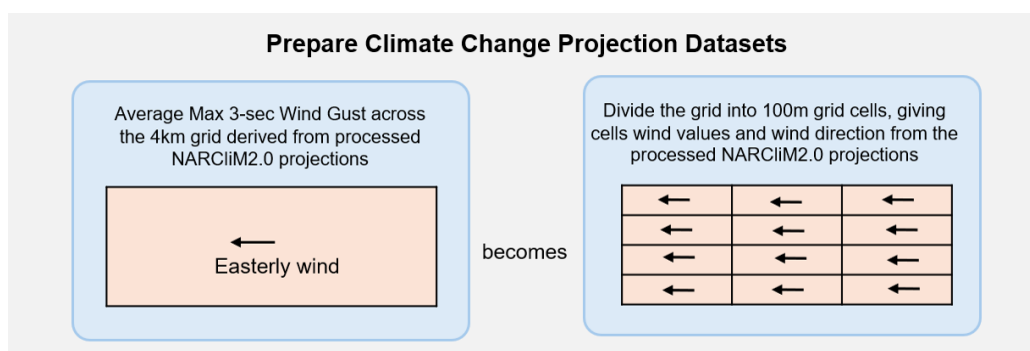


Figure 5 Preparing Climate Change Data

b) **Prepare the Terrain Scaling Factors**

- Use the WindNinja Momentum-Conserving model to calculate terrain scaling factors at 100m resolution relative to the average across the 4 km grid. This step is done independently to the climate change data set but uses the same 4 km spatial grid (Figure 6).
- 'Terrain Scaling Factors' are reasonably constant across the range of wind gusts that are relevant for asset failures but vary based on wind direction. Therefore, we repeat this process for all cardinal directions (N, NE, E, SE, S, SW). We call these the '**Terrain Scaling Factors**'.

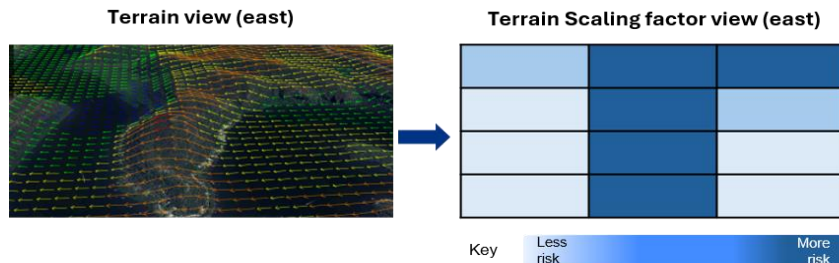


Figure 6 Preparing Terrain Scaling Factors

c) **Integrate the Climate Change Models and the Terrain Model**

- Multiply the 'Processed NARCLIM2.0 Projections' with the 'Terrain Scaling Factor' to identify sections of Ausgrid feeders with relatively higher and lower exposure to wind-related risk compared to using climate models alone.
- The processed NARCLIM2.0 projection provides the climate-change signal for each 4 km grid cell. WindNinja terrain scaling factors applied to the underlying 100 m cells preserve this climate-change signal while adjusting wind gusts to represent local acceleration and sheltering (Figure 7).

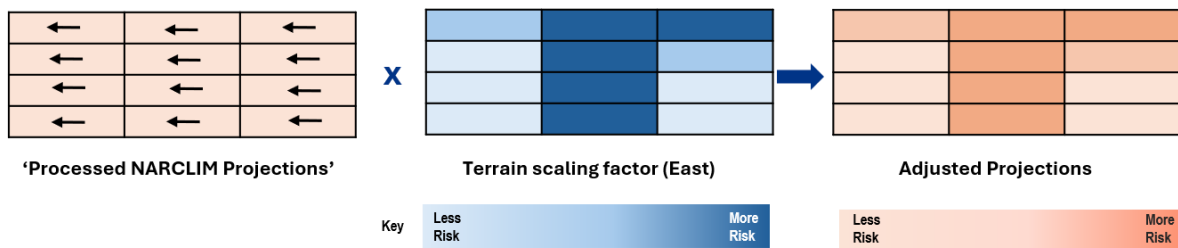


Figure 7 Combining Climate Change Projections with Terrain Scaling Factors

6. Discussion and Recommendations

NARClIM2.0 is a high-quality regional climate change dataset that should remain the primary source for understanding how wind hazards may change over time. However, its 4 km spatial resolution is too coarse to resolve many wind effects that influence distribution networks. These include ridge-top acceleration, valley sheltering, lee-side effects, exposure to prevailing wind directions, and other local variations in wind flow.

Terrain model WindNinja can translate regional wind information into high-resolution directional terrain scaling factor that represent how local topography modifies wind exposure. These scaling factors may increase or decrease regional wind speeds depending on the terrain response and can be applied at approximately asset-level resolution. This process is endorsed by academic literature and industry practice.

The key question raised by this paper is whether combining climate model outputs with a terrain dynamic model ('Integrated Approach') can better identify sections of feeders with relatively higher or lower exposure to wind-related risk than can be achieved using climate model data alone.

Ausgrid believes that it can be reasonably assumed that wind will continue to interact with hills, ridgelines and gullies in much the same way as it has done historically. Therefore, it follows that the wind flows modelled by Terrain models should remain largely plausible into the future.

Based off this assumption, combining climate datasets with terrain-based wind modelling provides a plausible way to differentiate comparative wind risk along a feeder than relying on climate datasets alone. Climate projections remain the primary source for understanding future changes in wind hazard; however, terrain modelling helps identify locations that are likely to experience relatively higher or lower exposure within a climate model grid cell. This additional insight supports targeted resilience investment and a risk-based approach to asset management.

It is important to recognise that the 'Integrated Approach' does not increase the accuracy, precision, or certainty of the underlying climate projections, nor does it create a fine-scale climate model. Rather, it integrates the climate change projections sets with terrain modelling to provide a physically based method for translating regional wind information into a more spatially detailed representation of local wind exposure.

Whilst this paper has focused on improving wind modelling by adding terrain modelling, it is important to recommend that other data sets such as vegetation and asset condition can also add to the body of knowledge used to understand wind related risk.

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