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Impact of forest gaps on wind turbulence and potential wildfire behavior at the rural-urban interface

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Abstract

Forest canopy can impact fire behavior through modulating both subcanopy atmospheric turbulence and wake turbulence at the forest edge. The 2020 Lake Ōhau fire happened at a rural-urban interface where the heavily fire-damaged village was surrounded by a heterogeneous forest canopy. Evidence shows that high wind speeds with strong gusts were present throughout the fire outbreak, indicating a strong wind-driven wildfire. Since the village was surrounded by complex terrain including a forest canopy, the forest canopy might play an important role in modifying the wind conditions within the village which could impact the fire spread behavior.

This research uses Large Eddy Simulation (LES) to study wind gusts and other near-surface wind characteristics in the Lake Ōhau area under the weather conditions of the 2020 Lake Ōhau fire. The work especially focuses on how the forest canopy around the village could change the wind gust within and around the village area. To do so, a LiDAR field campaign was also undertaken to obtain ultra-high resolution (grid resolution < 10m) forest canopy and other geoinformation.

Results also show that the village was impacted by two mesoscale wind systems - an offshore westerly downslope wind from west of the village and a northerly wind coming down over Lake Ōhau. The LES results were also used to further explore how simulated forest gap orientation might impact the downstream wind. Previous studies have shown that creating forest gaps or firebreaks can significantly change the wind characteristics within and at the edge of the forest. Three additional scenarios were studied by modifying the forest canopy around the village, including one without any forest canopy, one with horizontal (West-East orientation) forest gaps and one with vertical (North-South orientation) forest gaps. Total removal of the forest canopy increased the average wind gust in almost all areas within the village while the changes were spatially more heterogeneous in the horizontal and vertical gap scenarios. Differences of the spatial wind gust distribution might be related to how different forest gap alignments change the dominant inflow wind component. Next steps of this work will utilize passive tracers and temporal analysis to identify the processes driving these differences.

1. Introduction

The 2020 Lake Ōhau fire was one of the largest fires in recent New Zealand history with 54 residential buildings damaged and all residents forced to evacuate (Fire and Emergency New Zealand, 2021). The fire started at about 2.00am, October 4th local time (1.00pm October 3rd UTC) and burnt 5043 hectares of land in total. The extent of the fire can be seen in the short-wave infrared (SWIR) imagery from the Sentinel 2 satellite (Figure 1, the brown patches). The FENZ 2021 report highlighted the extremely high wind gusts (up to 167.2 km/h) measured at the closest automatic weather station (AWS) during the incident. The presence of such strong wind gusts suggests that atmospheric flow, especially surface atmospheric turbulence, will play an important role in the fire spread behavior.

The Lake Ōhau village settlement (Lat: -44.271, Lon:169.847) lies at the confluence zone of complex valley outlet systems to the west, the lake coastline to the north and east, and a relatively large pine forest to the northwest (Figure 2). With the complex terrain features (including topography and forest canopy) in this rural-urban interface, it is paramount to understand how these features modulated localized wind turbulence during the fire. Due to the limited on-site measurements (the closest long-term weather station is more than 50km away and situated in a different valley), high resolution turbulence-resolving numerical simulations are the best tools available to study the wind behavior.

Figure 1: The Lake Ōhau fire from Sentinel 2 satellite short wave infrared (SWIR) imagery, October 3rd 2020 (UTC).

This research focused on the forest canopy around the village. Studies have shown that both the vertical structure of the forest canopy and forest gap location can impact the fire-atmospheric interaction through modifying fire-induced atmospheric turbulence (Kiefer et al., 2016, 2018). Forest gaps or firebreaks can be naturally formed or intentionally created. They have been used in recent decades as a silvicultural tool to reduce wildfire risks (Scarascia-Mugnozza et al., 2000). Most studies on forest gaps or firebreaks focus on the efficiency of the gaps in delaying or stopping fire from spreading further. However, a few studies have investigated the role of forest gaps on wake turbulence and how the turbulence mixing and flow reattachment at the wake of the forest canopy can impact fire behaviors like ember transport (Chung & Koseff, 2021). These studies are mostly based on idealized simulations using homogenous (evenly distributed) vegetation canopy. Questions remain about how different alignment of forest gaps can impact the near-surface atmospheric turbulence within a highly heterogenic environment such as the rural-urban interface (RUI).

Previous studies have compared the Large Eddy Simulation (LES) to field measurements and shown that LES models with a vegetation canopy module is capable of simulating atmospheric turbulence within and at the wake of the forest canopy (Kiefer et al., 2022; Mueller et al., 2014). Thus, an LES model was used in this study to investigate the role of the forest canopy in modulating the atmospheric flow during the Lake Ōhau fire.

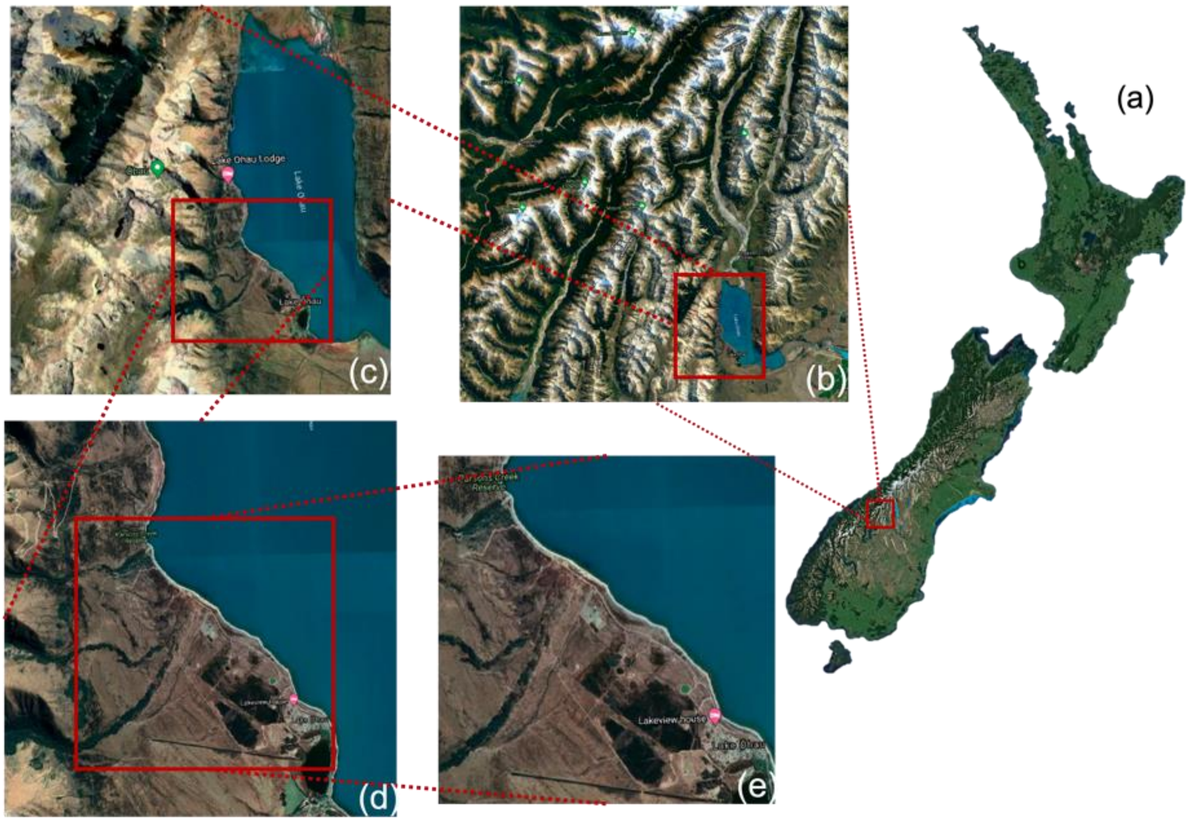

Figure 2 - Image of Lake Ōhau and surrounding topography from Google Earth. Areas from (b) to (e) are covered in our nested large eddy simulations as domain D2 to D5.

2. Methods

2.1. Mesoscale weather condition during the fire

Mesoscale weather information was obtained through the Weather Research and Forecast (WRF) simulation (Figure 3a). The simulation results aligned well the nearest AWS observation (Figure 3, the location is about 50km northeast of the Ōhau village). The AWS data was consistent with synoptic charts and showed a high intensity northwest downslope wind with hourly average wind speed around 10m/s during the event. The simulated mesoscale wind speeds on the majority of the downwind slopes of the region, as shown in Figure 3, were around 20m/s or greater

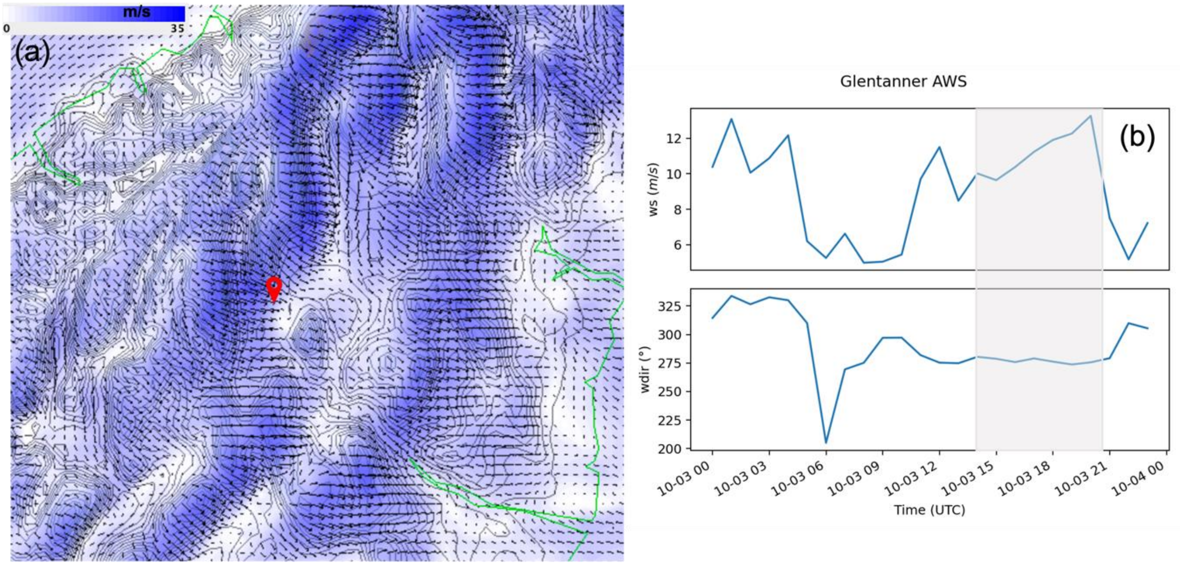

Figure 3- a) Hourly surface wind speed (10m AGL) at 2020-10-03 21:00 (UTC) from a 3km WRF simulation. The marker indicates the Lake Ōhau village area. b) Hourly wind speed and wind direction from the Glentanner AWS (-43.91498S, 170.12862E). The grey area indicates the fire ignition and early spread period.

2.2. Model description and initialization

The LES model used in this study is called the PALM model (B. Maronga et al., 2015; Björn Maronga et al., 2020; Raasch & Schröter, 2001). The model was set up using nested simulation domains with the second largest domain covering 62km in both horizontal dimensions around the Lake Ōhau area to allow a well-developed terrain-induced atmospheric inflow to the village area. The inner-most domain was focused on the Lake Ōhau village area with very fine horizontal (9m) and vertical (3m) grid resolutions to resolve the small scale near-surface atmospheric turbulence. The detailed domain configuration can be found in Table 1 and Figure 2.

Table 1. LES simulation domain setup. D1 domain was used to avoid numerical instability caused by steep terrain. For D2 and D3, the terrain information (DEM and land cover information) is taken from Land Information New Zealand (LINZ). For D4 and D5, merged terrain information was used based on both the LINZ datasets and our LiDAR field campaign. The vegetation and urban canopy were used only in the finer domains (D4 and D5). Detailed information can be found in section 2.2.2.

Domain name	**Domain size ($L_x \times L_y \times L_z$) (km)**	**Domain resolution ($\Delta x \times \Delta y \times \Delta z$) (m)**	**Terrain information**	**Vegetation and urban canopy**
D1	93×78×12	243×243×81	Flat and homogeneous	No
D2	62×62×10	243×243×81	Yes	No
D3	16×16×4	81×81×27	Yes	No
D4	5.8×5.8×1.3	27×27×9	Yes	Yes
D5	3.5×3.5×1.2	9×9×3	Yes	Yes

2.2.1. Field campaign and geoinformation reconstruction

To carry out an ultra-high resolution LES simulation, same-resolution geoinformation is needed including land cover information (vegetation type, urban land type etc.), leaf area density (LAD) profiles at all spatial locations, and urban building location and height information. The land cover information and urban building locations are taken from the Land Cover Database version 5.0 and NZ Building Outlines created by Land Information New Zealand (LINZ). The LAD and building height information is derived from the data obtained during our terrestrial LiDAR helicopter campaign. To simulate the pre-fire vegetation/urban canopy impact on the near-surface atmospheric turbulence, the work also reconstructed the pre-fire vegetation/urban canopy information (Figure 4 shows the detailed process). The reconstructed vegetation shows more consistency with the pre-fire satellite image from Google Earth (Figure 5).

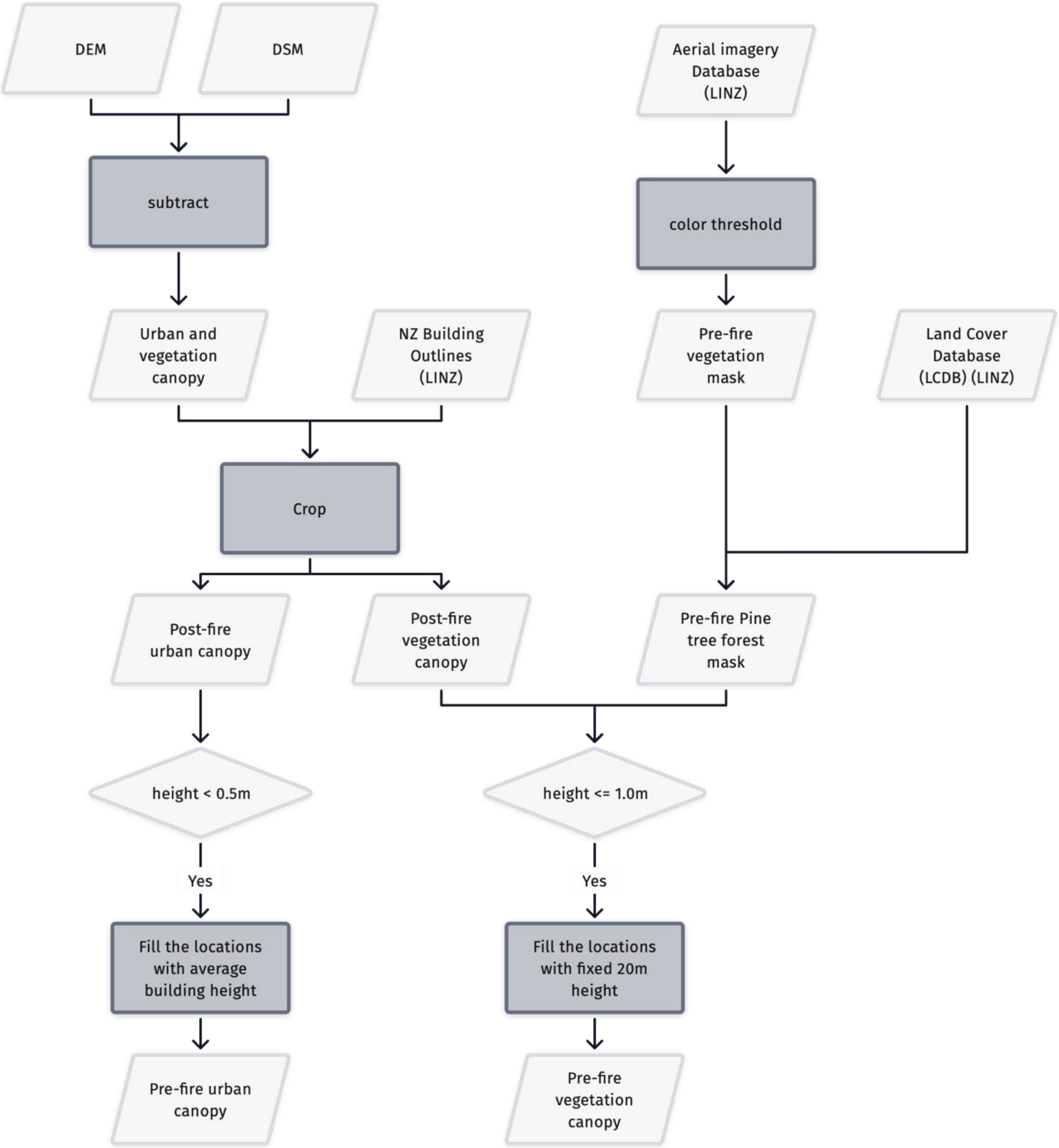

Figure 4- Process diagram - reconstructing the pre-fire vegetation and urban canopy.

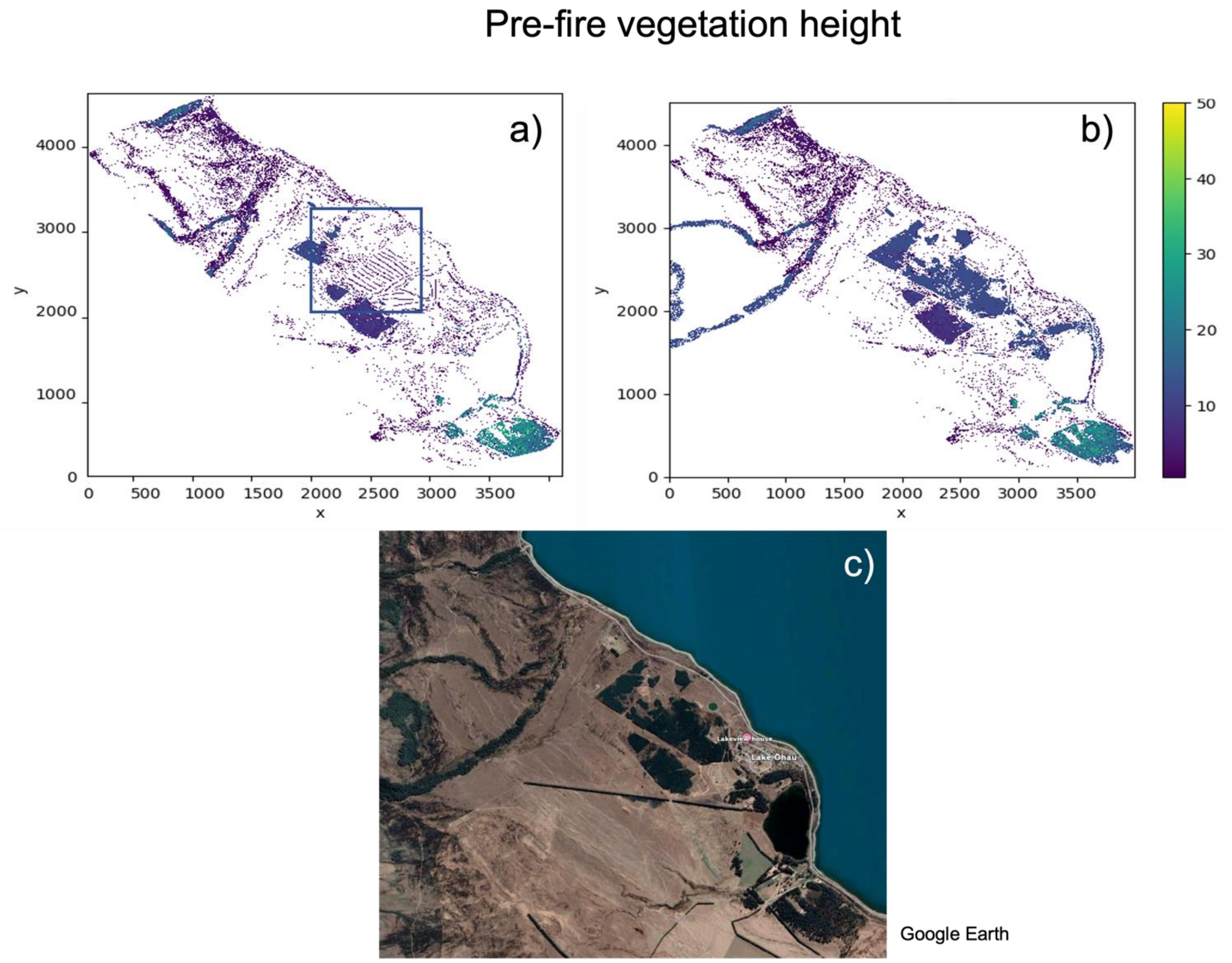

Figure 5- Vegetation height derived from LiDAR (a) reconstructed vegetation height (b) and pre-fire satellite image (c) from Google Earth image taken on 19/9/2019.

2.2.2. Simulation cases

Four scenarios were studied to address the impact of vegetation on the near-surface atmospheric turbulence during the fire: (i) the base case (Original) with the original reconstructed pre-fire geoinformation, (ii) all the vegetation around the village was completely removed (Noveg), (iii) 27m-wide horizontal (East-West orientation) gaps were created for all the trees around the village (Hgap) and (iv) 27m-wide vertical (North-South orientation) gaps were created for all the trees around the village (Vgap) (Figure 6). To incorporate the mesoscale forcing in the LES simulations, all the simulations carried out were initialized using average vertical profiles of velocity and temperature from the WRF simulation. In all scenarios, the LES model used the same initialization conditions from the WRF simulation data; the only differences being the modified vegetation canopy information. All simulations were run for 2 hours with the first 1.5 hours as model spin-up time. The last 30 minutes of data is analyzed below.

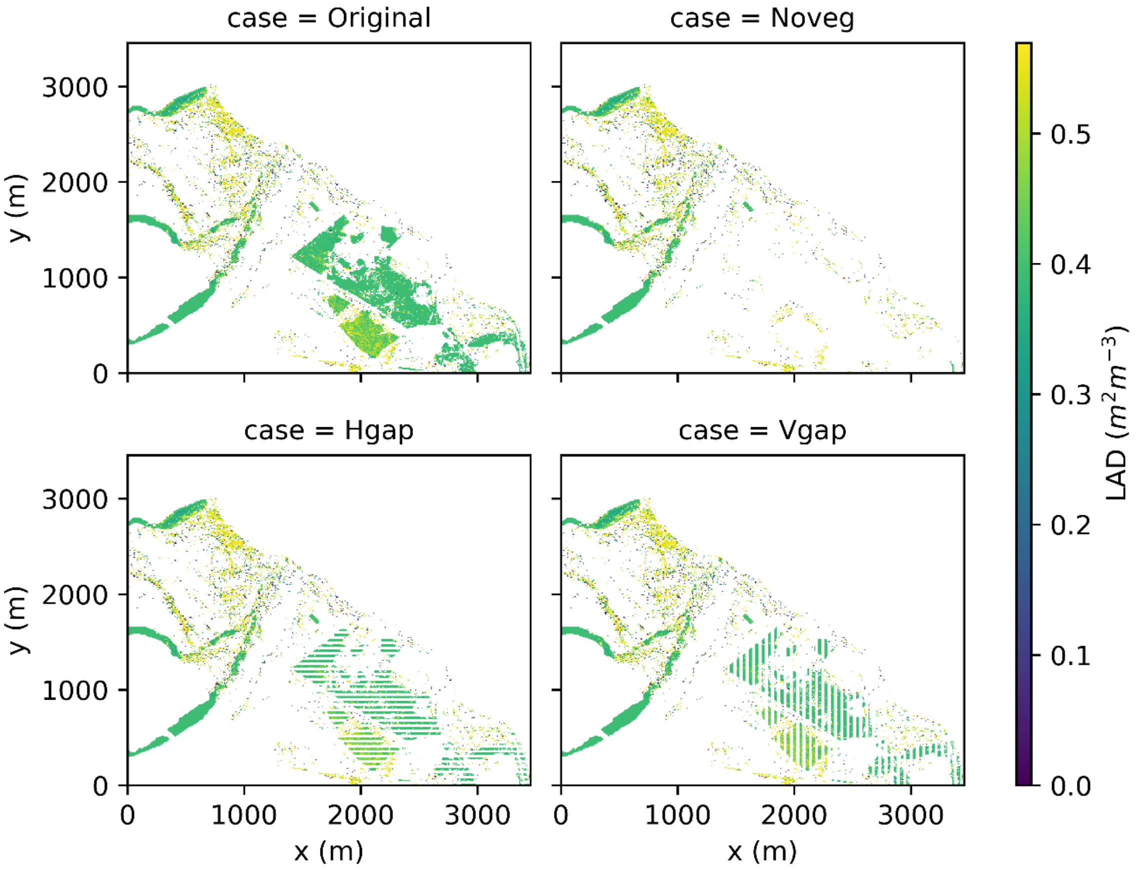

Figure 6- Leaf Area Density (LAD) at the first grid level above the ground (1.5m AGL) from four simulation cases. Original represents the original reconstructed pre-fire vegetation, Noveg represents removing all the trees around the village, Hgap represents the horizontal tree gap scenario, Vgap represents the vertical tree gap scenario.

3. Results and discussion

The base (Original) simulation shows that the village and the surrounding area were impacted by two main wind components. One is westerly downslope wind descending from the steep slope to the west of the village and the other one is the northerly down valley wind that traveled down across the lake (Figure 7). The result is consistent with the larger scale forcing from the WRF simulation.

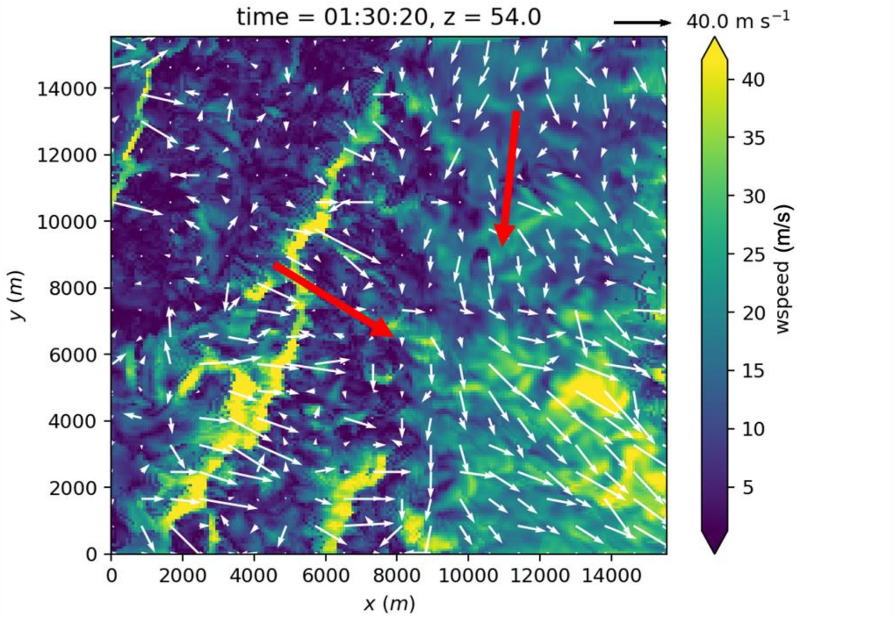

Figure 7- Instantaneous wind speed at 54m AGL from D3 domain. The red annotation shows two upstream incoming wind components that impacted the Lake Ōhau area during the fire event. Evidence of these two upstream wind components can be found from the instantaneous wind vector (white arrows) in the figure. Although not shown here, the two upstream components exist throughout the simulation.

Wind gusts are one of the important factors representing fire danger, especially in complex terrain where we still lack understanding of the spatial-temporal characteristics of wind gusts (Cheney & Sullivan, 2008; Letson et al., 2019). By simulating four different scenarios, the work found that modifying the vegetation canopy around the village can change the wind gust characteristics not only within the village but also in surrounding areas. Wind gust is calculated based on the World Meteorological Organization (WMO) standard (maximum value of the 3 second running average wind speed within one minute).

Figure 8 shows zoomed-in view of the differences in average wind gusts between the modified vegetation canopy simulations and the base case (Original) simulation from the D5 domain. Without surrounding vegetation (Noveg), almost all areas in the village experience an increase in wind gusts. A decrease in average wind gusts is only found in the wake of the buildings. This might indicate a more constant predominant wind direction resulting from the removal of vegetation which could act as a barrier to hinder the merging of the two wind components. Wind gust differences have more spatial variability in the horizontal forest gap (Hgap) and vertical forest gap (Vgap) simulations. The average wind gust is stronger in the central left area (solid boxes in Figure 8) in the Vgap scenario compared to the Hgap scenario. Both forest gap scenarios have weaker wind gusts in the bottom right of the village (dashed box in Figure 8). However, the wind gust decrease is more significant in the Vgap simulation than the Hgap one.

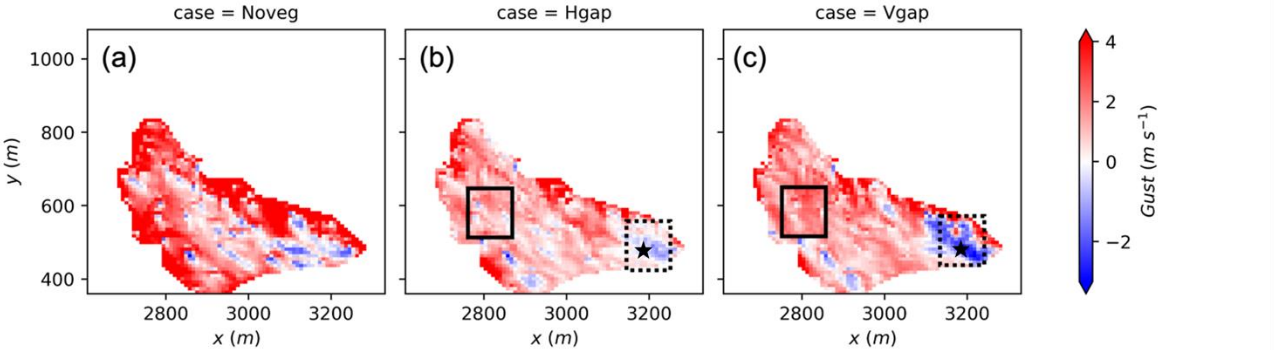

Figure 8- The difference of the average wind gust between each simulation with modified canopy and the base simulation during the last half hour simulation. Solid boxes in (b) and (c) show the area where the vertical gap simulation has stronger average wind gust compared to the horizontal gap simulation. The dashed boxes show the area where the horizontal forest gap simulation has stronger average wind gust than the vertical forest gap simulation. The star marker shows the location of which the wavelet analysis was carried out.

Areas with the average wind gust surpassing 30 m/s or 108 km/h can be found mainly over the lake area close to the village (Figure 9). Both the Noveg scenario and Hgap scenario have higher average wind gusts in the lake area while the Vgap scenario has similar wind gusts to the Original scenario.

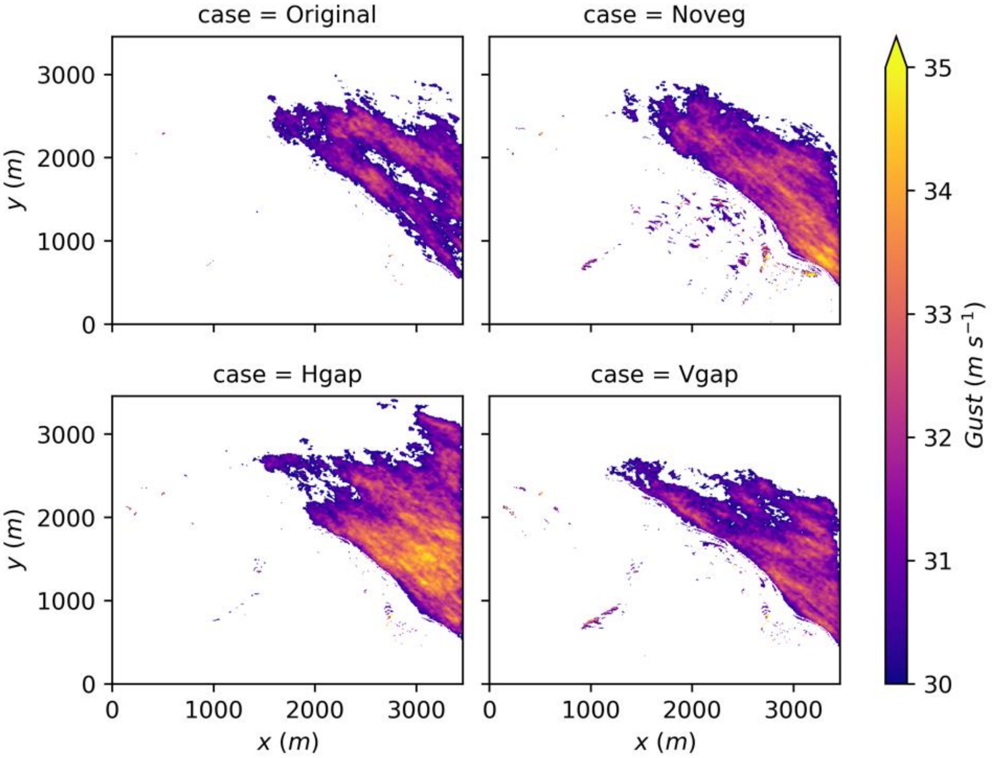

Figure 9- The average wind gust higher than 30 m/s at 6m AGL from the D5 domain.

4. Discussion and future work

The above results suggest that, with the two inflow wind streams (offshore westerly downslope wind and onshore northerly wind), different forest gap alignment might change the predominant inflow wind component by channeling one inflow stream and/or blocking the other. Time series analysis (Figure 10) shows slightly different integral scales between different forest gap alignments. At the selected location (star maker in Figure 8), the Horizontal gap (Hgap) scenario have more high frequency signals with period shorter than 32s (dashed blue line in Figure 10). This suggests more small-scale turbulence which might be caused either by shifting the predominant inflow components or locally generated turbulence coherent structures within the canopy. Further spatial/temporal signal analyses are needed to confirm the mechanism behind the spatial heterogeneity of the wind gust changes among different forest configurations. Future work will also use a passive tracer released at different sides of the forest patch edge (Figure 11) to further evaluate the fire risk (potential ember transport etc.) associated with atmospheric flow around the RUI.

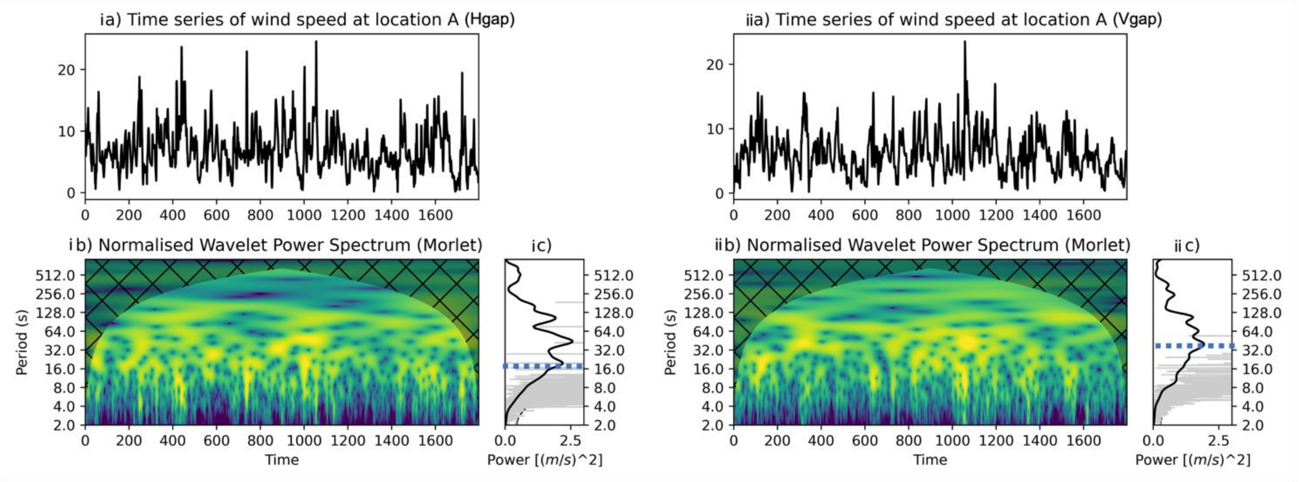

Figure 10- Wavelet analysis of the wind speed (1Hz) taken at the same location (star marker in Figure 8) for Hgap (left) and Vgap (right) simulations. ia) and iia) are the time series, ib) and iib) show the wavelet power spectrum using Morlet mother wavelet function, ic) and iic) show the global wavelet spectrum (black line, dashed blue line shows the first power peak) and Fourier power spectrum (grey line).

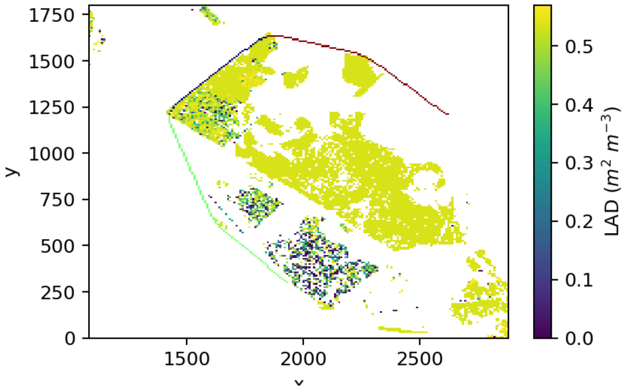

Figure 11- The passive tracer release location map. Green, blue and red curved lines indicate three different tracer groups that will be released at different sides of the vegetation canopy around the village. The rest of the image shows the leaf area density (LAD) at 7.5m AGL to indicate the relative location of the tracers to the vegetation canopy.

5. Conclusion

Preliminary results show that the vegetation canopy surrounding Lake Ōhau village can modulate wind gusts within and around the village. Removal of surrounding trees can alter the spatial wind gust distribution in different ways. In our case study simulations, the total removal of forest vegetation around the village resulted in increasing the average wind gusts of about 4m/s and higher in almost all areas within the village. On the other hand, forest gaps created through partial removal of the trees resulted in varying changes to the wind gusts in the village, depending on the direction of the gaps. Comparisons of the spatial distribution of wind gusts over the lake adjacent to the village also show that the influence of the vegetation canopy changes can extend far beyond the village area. Our current results suggest that the alignment of the forest gap might impact the dominant inflow component which might then impact the fire spread through changing wind speed and wind gust intensities, Further spatial and temporal analysis of the wind field and passive tracer distribution will help further verify these hypothesis.

6. Acknowledgement

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