Wind as an opportunity!

Mapping urban air systems in Rotterdam
a pilot study

December 2024

Gemeente Rotterdam

Actiflow

Colophon
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With funding from the Knowledge and Innovation Fund of the Municipality of Rotterdam

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Contents.

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1. Introduction.

We all want healthy, safe and liveable cities. While air is one of the factors of influence, within the Dutch spatial domain there happens to be little attention for 'urban air systems': how air moves through the city and causes, for example, wind nuisance or urban ventilation. Designers and policy makers often do not know how they can influence urban air systems, let alone use them to achieve the above ambitions. A missed opportunity! In this pilot study, we explore the potential of gaining insight into and working with urban air systems in Rotterdam, in a multidisciplinary setting. Let us share the results widely and use them to put this theme on the map and use it to its fullest potential!

Motivation

At the moment, many wind studies are already being executed in Rotterdam for individual buildings and urban developments, to determine whether wind nuisance and wind distress occur. Over the last years, the municipality of Rotterdam has been gaining a lot of new insights regarding this theme, which have served as input for the addendum to the High-rise Vision (June 2023) and the Manual for Wind Nuisance and Wind Distress in Rotterdam (April 2023). This has been a necessary first step to arrange safety and basic wind comfort in the city.

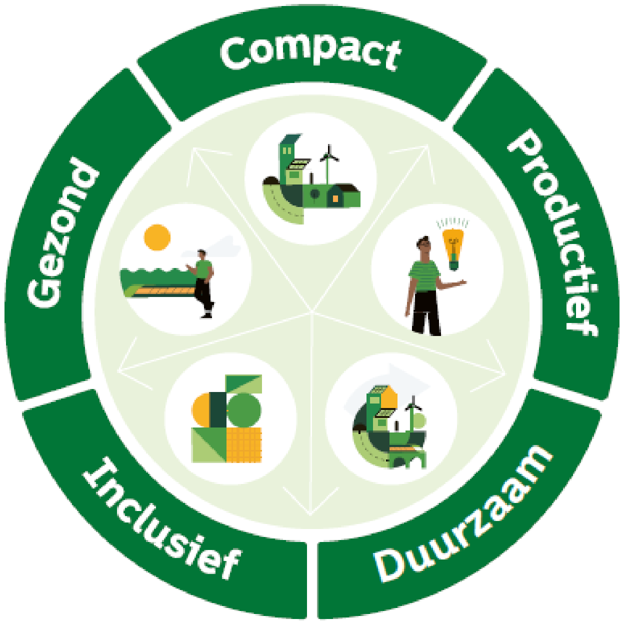
We often hire companies to carry out these complex, time-intensive wind studies according to the NEN8100 method: the Dutch standard for wind nuisance and wind distress in the built environment. In these studies, all wind flows around the buildings are being calculated, but we only extract two images from all this data: one image for wind nuisance and one image for wind distress. However, if the simulations have already been done, you could easily and quickly extract much more interesting information from them, for example about the potential of urban ventilation for heat stress and air quality or the suitability of roofs for wind energy.

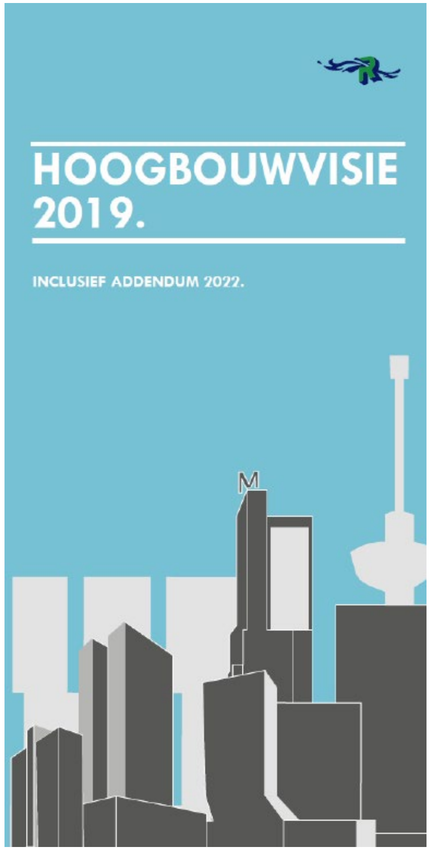
Process

In this pilot study, a wind study has been conducted for a large part of the city with different types of neighbourhoods (high-rise area, residential neighbourhood, harbour, park, etc.). The diameter of the research area is approximately 5 kilometers. This allows us to – for the first time – look beyond merely the high-rise areas and gain more insight into how wind behaves in the rest of the city. The wind simulations were carried out by Actiflow, an engineering firm specialised in wind studies.

Subsequently, brainstorming sessions were held with a multidisciplinary group of designers and policymakers within the municipality (urban design, landscape architecture, planning, energy transition, air quality, heat, data, technology). Based on the initial research results, we explored what other interesting information could be obtained from the study. These were valuable and inspiring sessions, in which many new ideas and opportunities emerged, which Actiflow then incorporated into the next steps.

The process offered a lot of freedom to collaboratively explore how the pilot study would develop. It was an experiment and an iterative process; the end goal was not fixed. This has resulted in even more interesting and surprising insights than we had anticipated beforehand. This report presents the results of the pilot study. Chapter 2 discusses all the maps created and the lessons we can learn from them per theme.





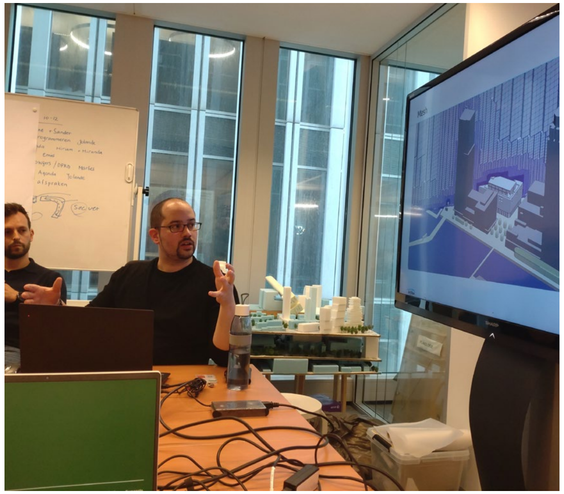
In policy documents such as the Environmental Vision (above) and the Rotterdam Weather Report (below), air has not (yet) been explicitly included as a theme

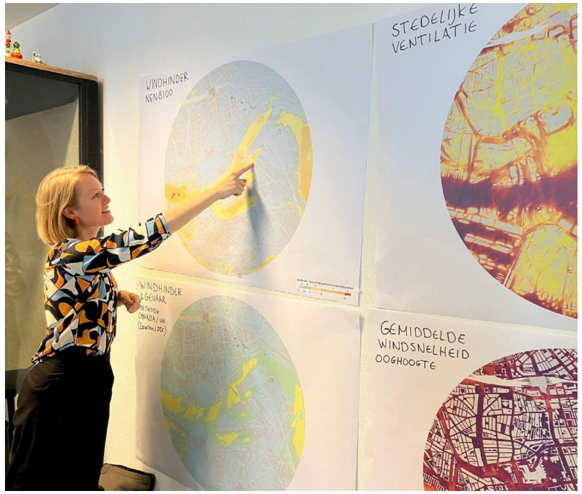
The addendum to the High-rise Vision and the Wind Nuisance and Wind Danger Manual contain guidelines for preventing wind nuisance and danger.

Chapter 3 summarises the conclusions. The technical explanation, intended for people who are curious about the technical specifications or who want to repeat certain parts, can be found in Chapter 4. Enjoy reading and get inspired!

Introduction summarised:

- Goal: healthy, safe and liveable cities.
- 'Urban air systems' have a lot of potential, which often remains underused.
- We already do many wind studies, but we get very little information from them; that is a waste of potential.
- For the first time, we are doing a study on a larger scale, including multiple districts and areas at the same time instead of separate buildings/urban developments.
- We brainstorm with a multidisciplinary group of experts about the opportunities and next steps.
- Many interesting and surprising insights emerge!





Photos of the brainstorming sessions with the wind experts from Actiflow and a multidisciplinary group of designers and policy makers from the municipality of Rotterdam

Research area
aerial photo

2. Results.

In this chapter, the results of the simulations are discussed per theme. We start with wind nuisance and wind distress. In addition to the usual wind study results, we also look at the differences between summer and winter and the use of other (international) assessment methods than the NEN8100. Then we move on to a new theme: urban ventilation. This is linked to heat stress and air quality. We look at the ventilation potential of the city, a breeze on hot days and at the way in which particulate matter from a busy car street spreads through the surrounding urban fabric. We then discuss the potential of inner-city roofs for generating wind energy. And finally, we show how the wind moved through Rotterdam during a number of recent storm days. This last theme was the biggest surprise of this pilot study!

The simulation

To understand the results, we will first explain how they were achieved. There are two reliable methods for conducting wind studies: the wind tunnel and CFD (Computational Fluid Dynamics; computer simulations). Since a scale model of the area does not physically fit in a wind tunnel, we chose CFD. This is a method for conducting wind studies using a computer. A wind study based on CFD simulations consists of several steps:

1. The 3D model was created by Actiflow based on open source data and data provided by the municipality. With regard to the buildings, existing buildings were included as well as all buildings that are already under construction or have been granted a permit before April 2024. The building volumes have been slightly simplified. Private outdoor spaces have largely been removed from the model and building details smaller than 1 meter have been neglected; in the case of wind, this does not have much influence on the results. Vegetation has only been included if it concerns larger vegetation clusters. The outer edge of 250 meters (blue buildings in the image) is not part of the research area, but has been modelled to allow the wind to flow into the model in a correct way.
2. The model was then prepared by Actiflow to be able to perform the simulations. The air above and between the buildings was divided into cells: the calculation mesh. Due to the size of the area, the mesh for this study contains a total of more than 583 million cells; that is approximately 20 to 30 times as many cells as a typical study for a single building project. A lot of computer power was needed for the calculations. This has only become possible in recent years. The wind flows were calculated cell by cell, several times, ultimately determining the occurring air flows in the model. This process was repeated 24 times: two simulations were performed per wind direction, 12 in total (summer and winter). It took several days for the computers to finish calculating.
3. The final step is processing the results into readable images. During the brainstorm sessions, it was determined which data would be extracted from the simulations and how it would be visualized. Actiflow then created the images. This resulted in a whole series of maps, all based on this one series of simulations.

The 3D model, simulated by Actiflow in consultation with the municipality of Rotterdam

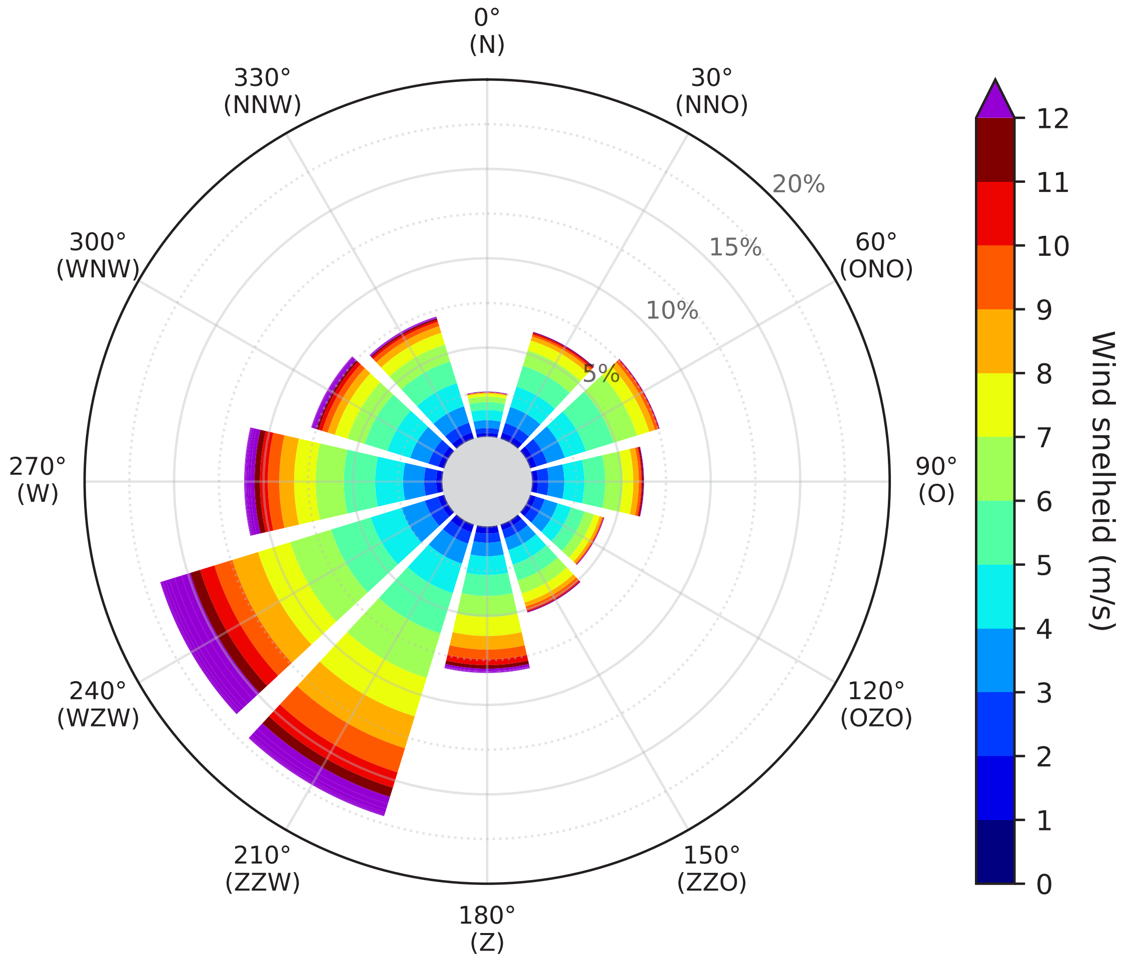
The wind rose

The NEN8100 stipulates that the meteorological KNMI data (Dutch Royal Meteorological Institute) from the NPR6097 (application of the statistics of the mean wind speed for the Netherlands) must be used in Dutch wind studies. This is data from the period 1963-2002. The KNMI also has a more recent dataset: the Dutch Offshore Wind Atlas (DOWA), with data from 2008-2017. In addition to being more recent, this data is also easier to edit. For example, you can split it up by season, month or day, which is useful for this pilot. The data can be processed into a wind rose that indicates how often which wind directions and wind speeds occur in the year. Both datasets provide comparable wind roses, with the strongest and most frequent wind clearly coming from the southwest. Due to the above-mentioned advantages, it was decided to work with the most recent dataset. All maps in this report are therefore based on this. In order to enable comparisons with previous wind studies, the maps for wind nuisance and distress based on the old data are included in the appendix (in accordance with NPR6097).

Annual average wind speed

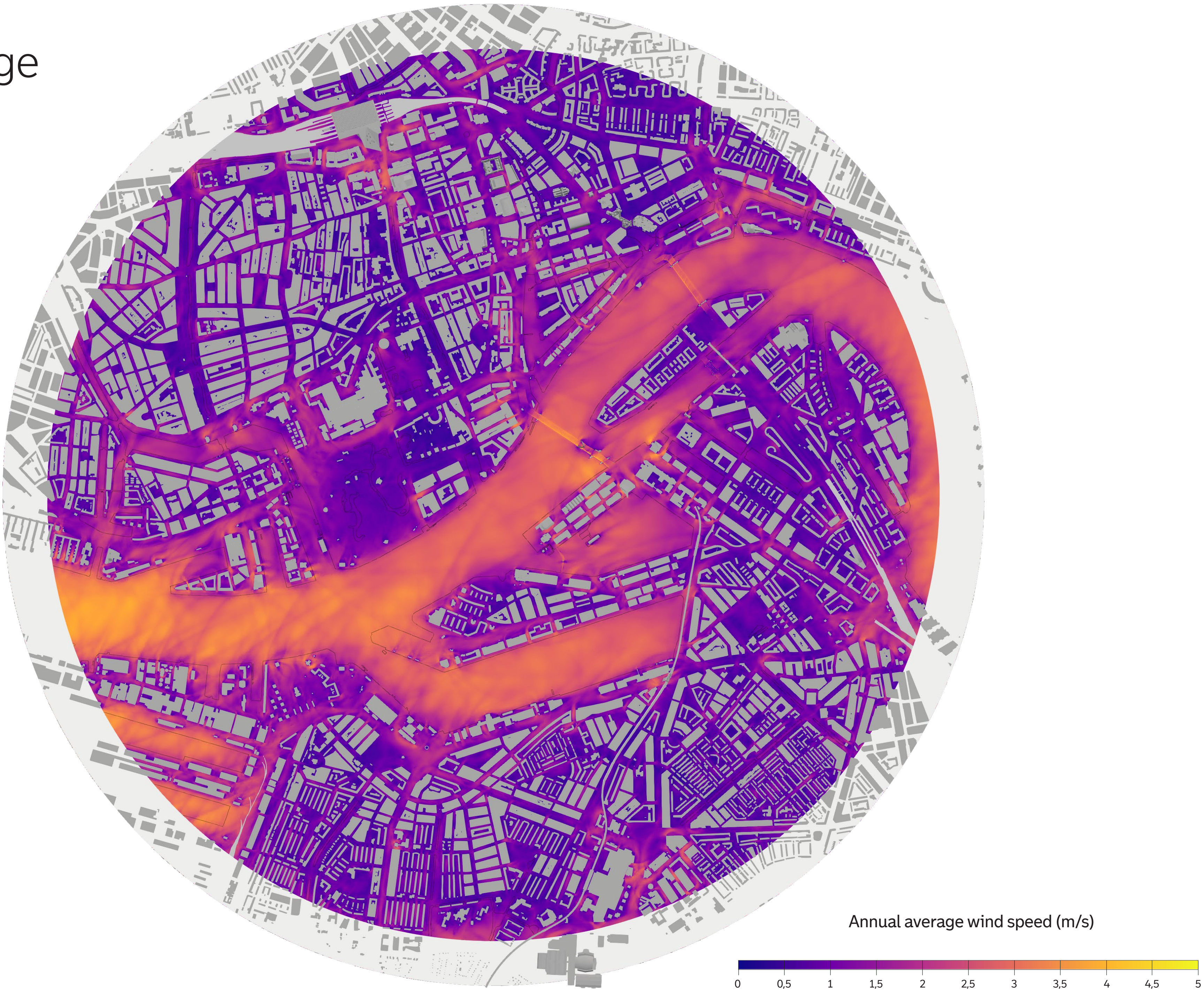
Combining the simulation results with the wind rose, it is possible to determine the annual average wind speed. On the map, you can see this annual average wind speed at eye level (1.75 meters). We can directly draw the following conclusion:

- The average wind speed above the river is way larger than in the rest of the city.



Local wind statistics: wind rose with recent meteorological data 2008-2017 (DOWA)

Wind speed
annual average

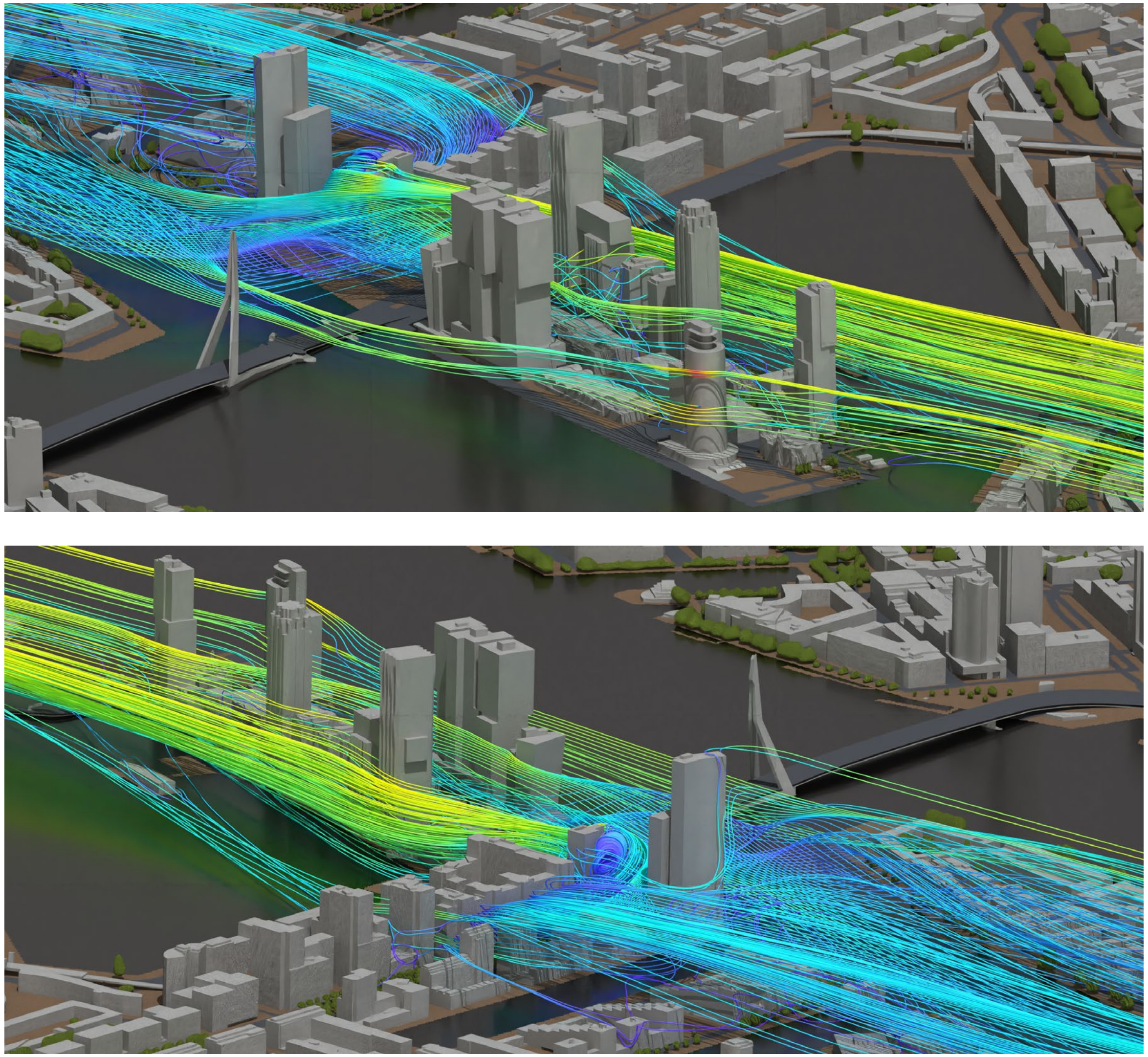


Wind flows in 3D

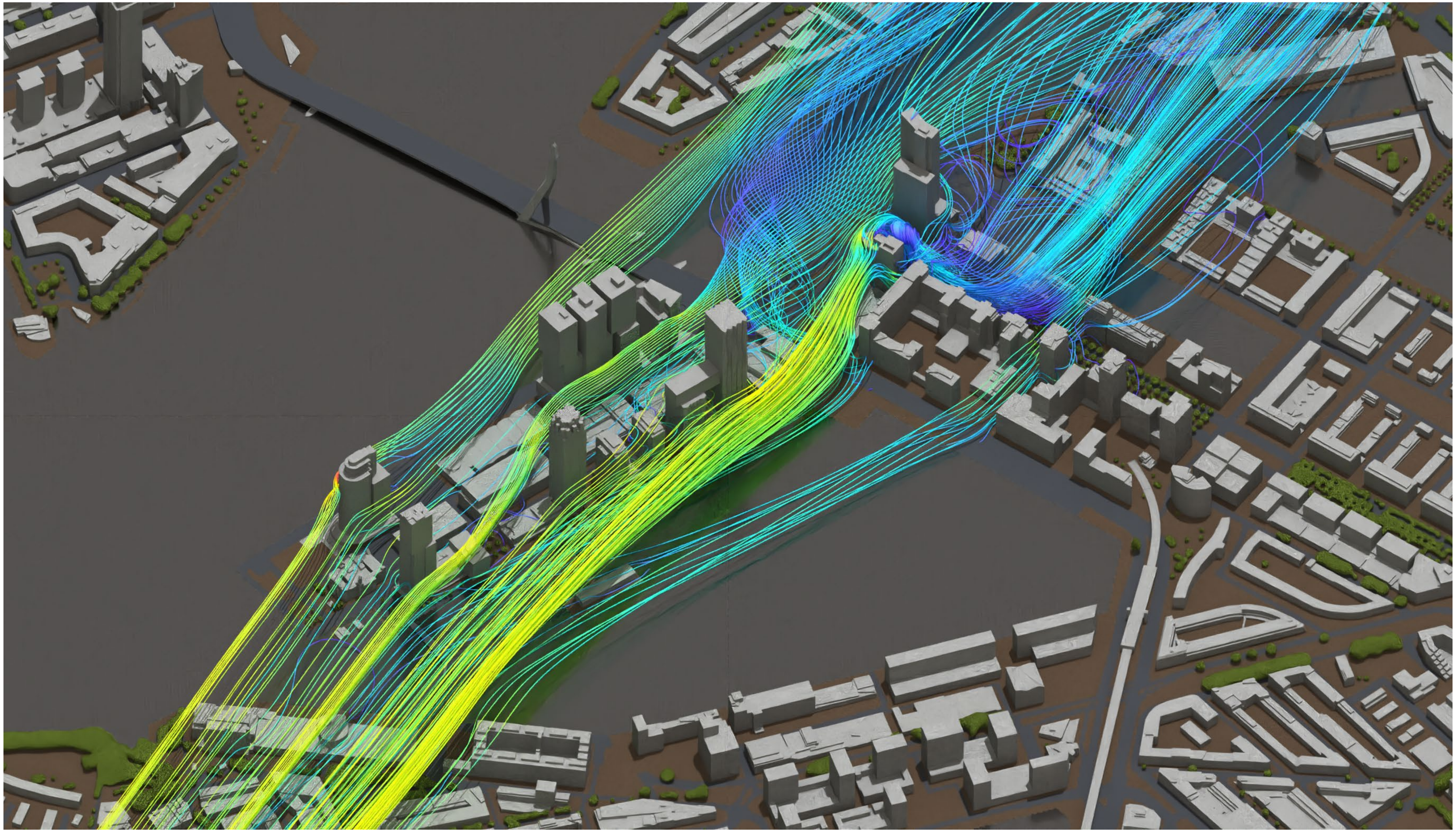
To get a feeling for how the wind moves around the buildings in the city, a number of 3D images were made for the area Kop van Zuid (center of Rotterdam). You can clearly see how the buildings direct the wind in a certain direction. You can also see how the wind hits the Maastoren (the highest tower), is guided downwards (downdrafts) and accelerates strongly around the corner at eye level (corner streams). This is a well-known Rotterdam spot where cyclists and pedestrians have to deal with strong winds. The spot also has a yellow colour on the map with the annual average wind speed.

Introduction of the results summarised:

- The simulations were made using CFD (Computational Fluid Dynamics).
- From one series of simulations you can make many different maps and images; which ones were determined during the brainstorm sessions.
- The wind rose used is based on the most recent meteorological dataset of the KNMI.
- Above the river the annual average wind speed is relatively high.



3D images of wind flows around the Maastoren in the Kop van Zuid area, with a south-westerly wind direction



2.1 Wind nuisance and wind distress.

In this section the results of the themes wind nuisance and wind distress are discussed. These are the themes that are commonly included in wind studies in the Netherlands. We start with the two 'standard maps': wind nuisance and wind distress according to the NEN8100 method. We then experiment with the division of summer and winter and with the application of another (international) assessment method.

Reliability of the results

It is important to mention in advance that the results of this pilot may show (small) differences with previously performed simulations. The reasons for this include that a larger area has been calculated (the impact of which needs to be further investigated), more recent wind data has been used and the buildings and vegetation in the 3D model may differ slightly from previous studies. The results of this pilot are therefore reliable enough to draw conclusions on a city scale, but should not be used to question previously performed studies and conclusions and policies.

Wind distress according to NEN8100

Wind distress is the occurrence of such a high wind speed that people experience major problems when walking (loss of balance). This occurs at an hourly average local wind speed of 15 m/s or higher. The map on the right shows where in the city wind distress occurs. The results are at eye level: 1.75 m height. The assessment was carried out in accordance with the NEN8100. The map shows how likely it is that wind distress will occur at a certain location, in other words: what percentage of the number of hours per year the threshold value for wind distress (15 m/s) is exceeded. Based on this percentage, the location is classified as 'no risk', 'limited risk' or 'dangerous', see the table. A 'dangerous' wind climate is unacceptable; 'limited risk' can be accepted in some cases.

Exceedance probability (Local wind speed > 15 m/s) (% of the amount of hours per year)	*Classification*
< 0,05 % (< 4,5 hours)	No risk
0,05 - 0,30 % (4,5-26 hours)	Limited risk
> 0,30 % (> 26 hours)	Danger

Legend assessment of wind distress according to NEN8100: what percentage of the number of hours per year is the threshold value for wind distress (15 m/s) exceeded?

Conclusions:
- For the vast majority of the area, there is no risk of wind distress.
- There are a few locations that are classified as 'dangerous': the Erasmus Bridge, parts of the Willems Bridge and the area directly next to the Lloyd Tower. Both bridges have an exposed location above the river, the place in the city where the highest wind speeds are reached. The Lloyd Tower also has an exposed location along the river bank and, at 70 metres, is considerably higher than the surrounding area. It catches a lot of (strong) wind, resulting in downdrafts causing wind distress at pedestrian level.
- The areas where a 'limited risk' has been calculated are spread throughout the city. These

Wind distress
according to NEN8100
annual average

areas each have a size of up to a few tens of metres and are mainly located around the Schiecentrale, the Kop van Zuid and Katendrecht (high-rise buildings directly along the water) and the Delftse Poort (high-rise buildings not located along the water).

Wind nuisance according to NEN8100

The map below shows where in the city wind nuisance occurs. The results are at eye level: 1.75 m height. The assessment was carried out according to the NEN8100. The wind nuisance value shows what percentage of the number of hours per year the threshold value for wind nuisance (5 m/s) is exceeded. Based on this percentage, the location is given a wind nuisance class: A, B, C, D or E; see table. A stands for the most windless climate and E for the most windy. For each wind nuisance class, it is described for which activity this location is suitable: sitting, leisurely walking or business walking.

Conclusions:

- Most of the city shows wind nuisance class A. Usually, there is little class A to be seen in the results, but that is because we normally only calculate risk areas (e.g. around high-rise buildings).
- The relationship between high-rise buildings and wind is clearly visible. Around freestanding high-rise buildings (with few to no mitigating measures) the wind speeds are relatively high, for example at the Maastoren, the Kop van Zuid and the area around the central station. However, you can also see this effect at a smaller tower in Charlois (residential, mainly a low-rise neighbourhood). The use of strategic design measures, such as set-backs and clustering of high-rise buildings, reduces this effect. This is visible, for example, at the Wijnhaveneiland area, which is almost completely class A despite the high-rise buildings. The building the Modernist also seems to have a large effect: in previous studies, the street Weena showed class D-E, but this strategically placed building (which was included in this pilot) seems to partly cancel out the acceleration of the wind between the existing high-rise buildings.
- It is striking that there appears to be relatively much wind nuisance on the Lloydpier. This location is comparable to the Kop van Zuid in terms of wind nuisance, while none of the buildings are higher than 70m. The reason for this is that the wind from the southwest flows almost unhindered over the Waalhaven (low industrial buildings) and river. The Lloydpier is not an official high-rise area, so it got way less attention from designers and policymakers who are concerned with wind, but that appears to be unjustified.

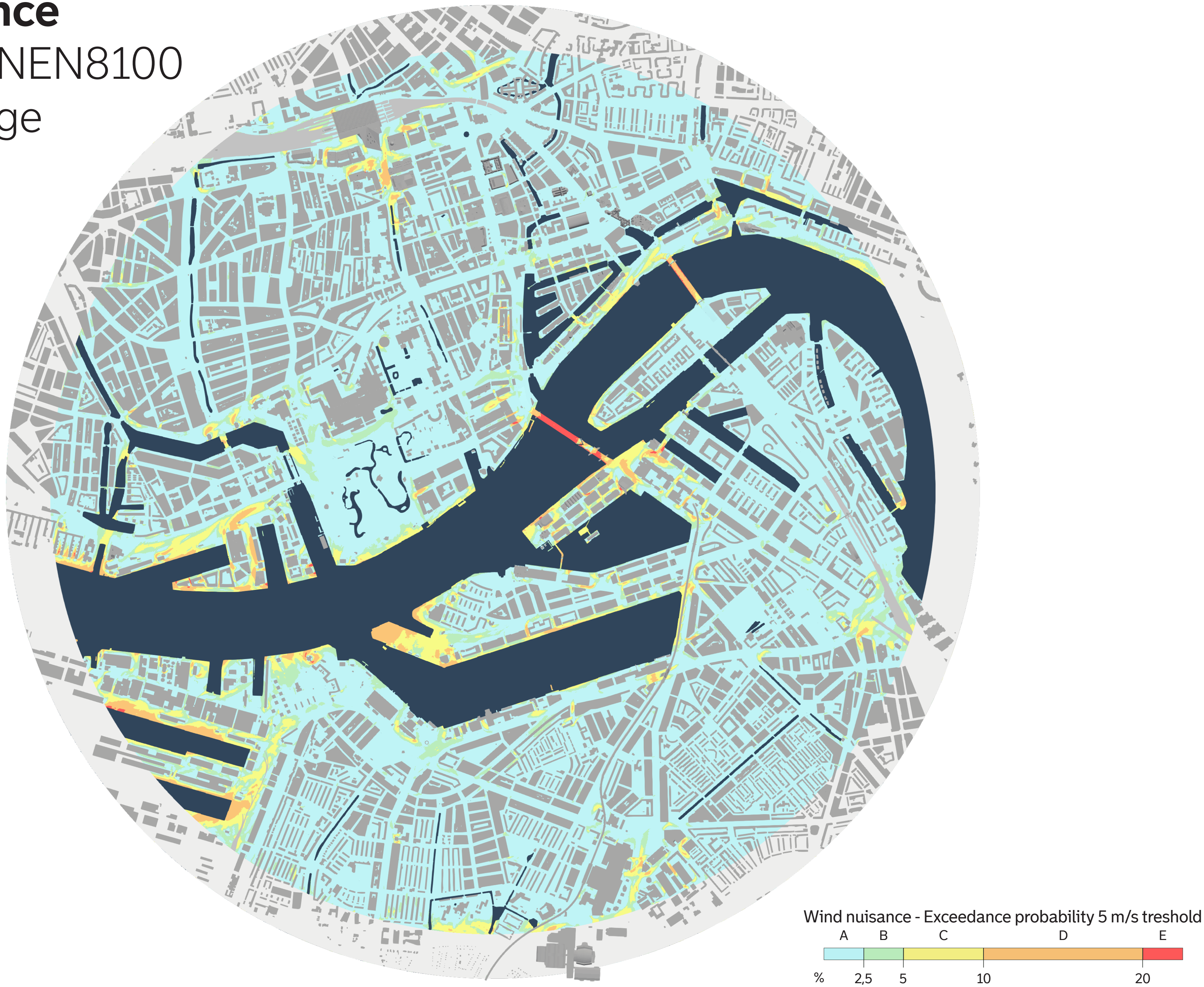
It is interesting to compare the results to:

- The height map (heights of buildings)
- Information about where terraces/playgrounds/ benches etc. are: then you can see which of these are strategically placed in terms of wind. Are they also used better/worse?
- Waste containers: are these strategically placed so that waste does not get blown away?
- Tree health (e.g. via infrared data or tree population): there is undoubtedly a relationship between wind and the growth conditions of trees. You can see this, for example, at the Fenixloods in Katendrecht, where two trees grow poorly; they appear to be exactly in the corner stream. The choice of certain vegetation types could also be based more on the wind conditions.

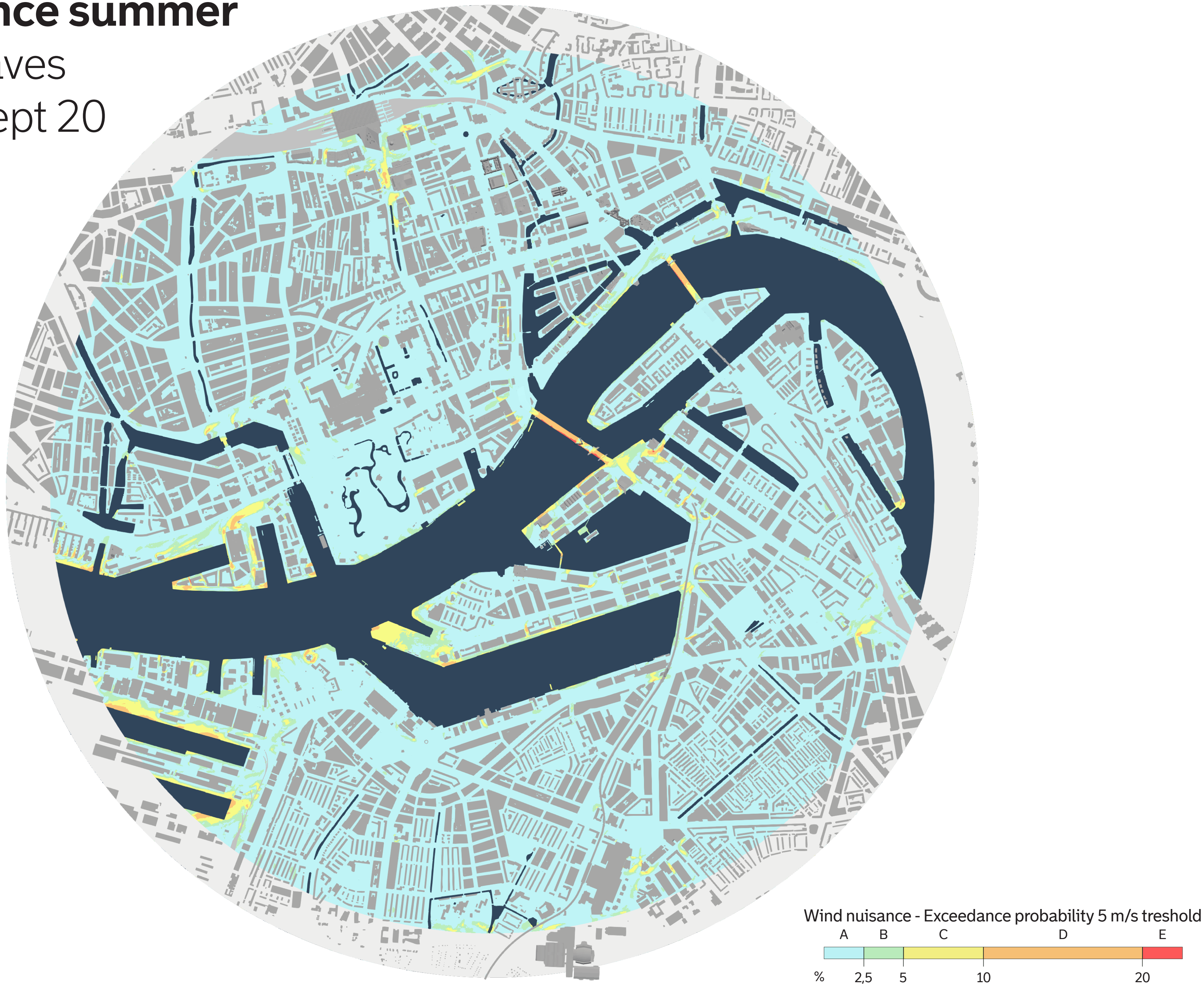
Exceedance probability (Local wind speed > 5 m/s) (% of the amount of hours per year)	*Wind nuisance class*	*Classification per activity*		
		Business walking	*Leisurely walking*	*Sitting*
< 2,5 % (< 219 hours)	A	*Good*	*Good*	*Good*
2,5 - 5 % (219-438 hours)	B	*Good*	*Good*	*Moderate*
> 5 - 10 % (> 438-876 hours)	C	*Good*	*Moderate*	*Bad*
> 10 - 20 % (> 876-1752 hours)	D	*Moderate*	*Bad*	*Bad*
> 20 % (1752 hours)	E	*Bad*	*Bad*	*Bad*

Legend assessment of wind nuisance according to NEN8100: what percentage of the number of hours per year is the threshold value for wind nuisance (5 m/s) exceeded?

Wind nuisance
according to NEN8100
annual average



Wind nuisance summer
trees with leaves
March 21 - Sept 20



Wind nuisance winter
trees without leaves
Sept 21 - March 20

Wind nuisance seasonal, divided into summer and winter periods

On the previous pages, the wind nuisance map is split into two maps: summer and winter. The assessment method is the same, except that the percentage on both maps is taken over half a year instead of the entire year. In addition, leafy vegetation is assumed for the summer period. Leafless vegetation is assumed for the winter period.

Conclusions:

- The south-westerly wind directions are dominant in both the summer and winter periods. High wind speeds occur more often in the winter than in the summer.
- The summer period is therefore less windy than the annual average; the windiest areas are often at least one wind nuisance class lower. The size of areas with class C and D has shrunk considerably. Class E hardly occurs.
- In the winter period, there is clearly more wind than in the annual average. Class C, D and E are all more common.
- The NEN8100 does not distinguish between summer and winter, while the use of public space in the Netherlands varies greatly per season. Showing the summer and winter seasons separately would therefore certainly be interesting.

Wind nuisance according to the English method: Lawson criteria

The last map of this paragraph (below) shows what the wind nuisance results look like if you do not visualize them according to NEN8100, but according to the Lawson method. Worldwide different standards exist for the assessment of pedestrian level wind comfort. Lawson is a well-known assessment method that is widely used in countries such as England and Canada. The method uses different starting points and therefore produces different results. In the Lawson criteria, a separate threshold speed is linked to each

Wind nuisance
English method
(Lawson criteria)
Yearly average

activity. This threshold speed may not be exceeded during more than 5% of the number of hours per year, see the table. This differs from the NEN8100, where a single threshold speed of 5 m/s is tested and the suitability of the wind climate for activities is determined based on the exceedance probability (how often the threshold value is exceeded). An assessment according to the Lawson criteria can therefore more directly determine at which locations the wind speeds will be higher. The NEN8100, on the other hand, shows how often the wind speeds are high enough at a location to experience wind nuisance.

Wind speed threshold	Exceedance probability threshold	Classification
> 15 m/s	≤ 0.025 %	No risk
> 15 m/s	> 0.025 %	Distress frail
> 20 m/s	> 0.025 %	Distress all

Legend wind distress assessment Lawson

Wind speed threshold	*Exceedance probability threshold*	*Classification per activity*
> 4 m/s	≤ 5 %	Sitting
> 6 m/s	≤ 5 %	Standing
> 8 m/s	≤ 5 %	Leisurely Walking
> 10 m/s	≤ 5 %	Business Walking
> 10 m/s	> 5 %	Uncomfortable

Legend wind nuisance assessment Lawson

Conclusions:

- In the case of Lawson, the results show less distinction than can be seen in the wind nuisance map according to NEN8100. The most unfavourable classes are also shown less. This can easily be explained by the fact that all activities, with the exception of sitting, are tested against a higher threshold speed.
- A relatively small zone on the Erasmus Bridge is the only place in the research area that is designated as 'uncomfortable'. The rest of the area is largely at least suitable for 'leisurely walking' according to the Lawson criteria. The definition of this is equivalent to 'strolling' according to the NEN8100. This is striking because it is known in Rotterdam that there are more places in the city that are certainly not comfortable for strolling. It is therefore questionable whether this assessment according to the Lawson criteria sufficiently corresponds to our experiences and the reality in Rotterdam.

Wind nuisance and distress summarised:

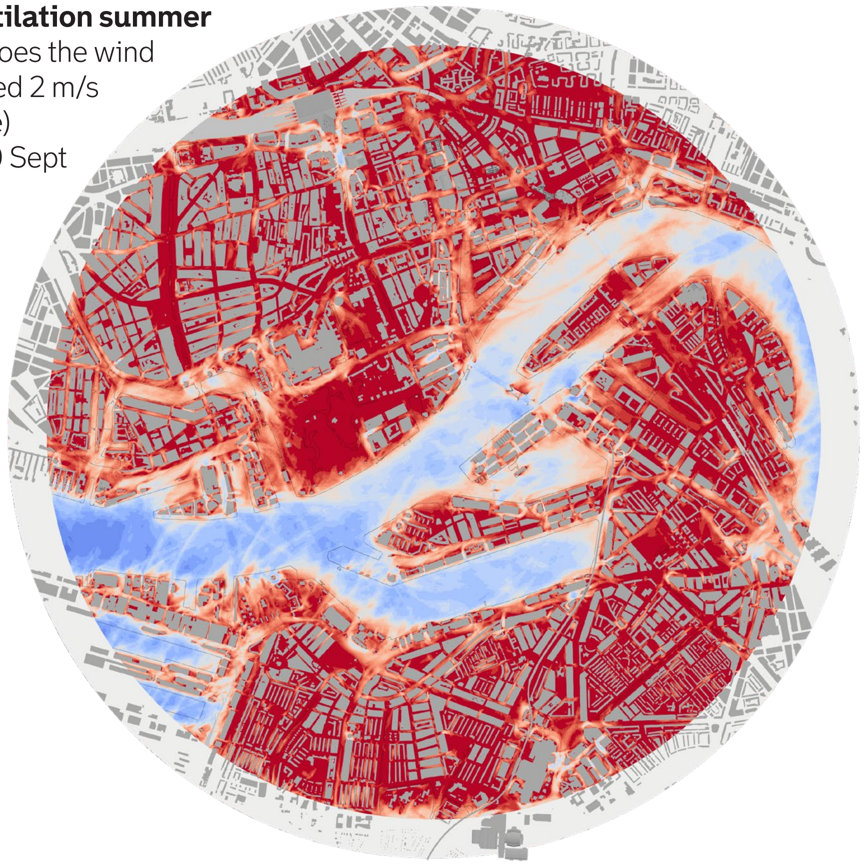
- Wind distress ('dangerous' according to NEN8100) hardly occurs in the area. 'Limited risk of wind distress' does occur, mostly along the river and/or around high-rise buildings.
- The largest part of the area has wind nuisance class A (the most windless). In a number of zones, much more wind nuisance occurs, mostly along the river and/or around high-rise buildings. The bridges, the Kop van Zuid, the area around the central station and the Lloydpier stand out.
- It is interesting to overlap this data with data on, among other things, building heights, places to sit, waste containers and vegetation.
- It is possible and useful to look at the summer and winter seasons separately, because the use of public space in the Netherlands varies greatly per season. On average, there is less wind in summer and more in winter time.
- The English method, Lawson, assesses wind nuisance and wind distress differently from the NEN8100. The results seem too positive compared to our experiences in reality.

2.2 Urban ventilation: heat stress and air quality.

Wind is not just a source of nuisance and distress, it can also have a positive influence. On hot days, for instance, a cool breeze can be very pleasant. Literature shows that wind contributes greatly to people's perception of temperature. Places with little shade but plenty of wind can therefore still feel pleasant on a hot day. In addition, wind can also ensure that particulate matter from a busy motorway is blown out of the street or actually stays there. In this section, we explore the potential of urban ventilation for reducing heat stress and improving air quality in the city.

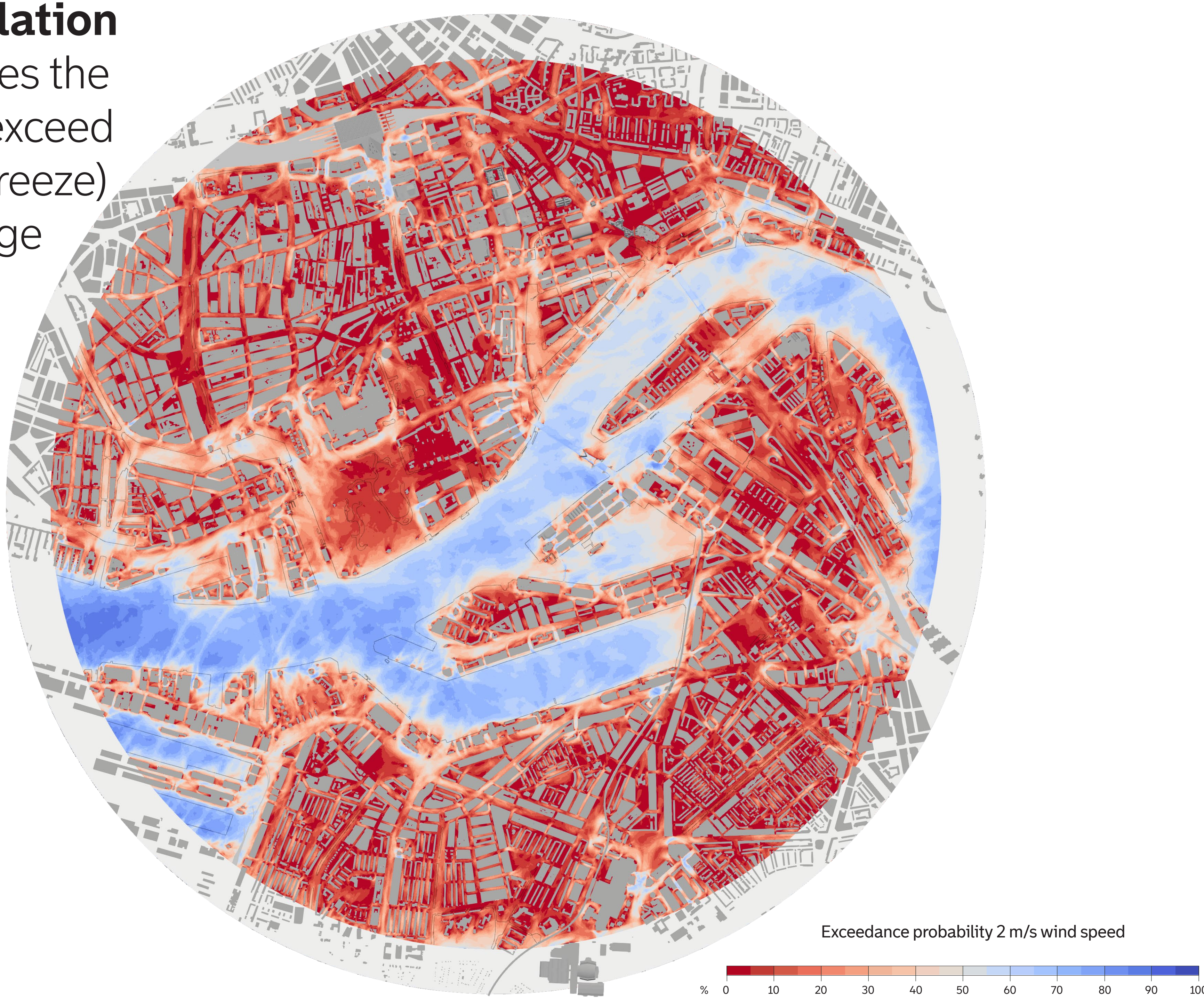
Urban ventilation: a cool breeze
Literature suggests that a minimum wind speed of 2 m/s is needed to effectively ventilate heat or air pollution from a street. The maps on the right, therefore, show how often (percentage of time) the wind speed exceeds 2 m/s. One map shows the annual average, while the other is limited to the warmest - and thus most relevant - summer months from June to September.

Urban ventilation summer
how often does the wind speed exceed 2 m/s (cool breeze)
21 June - 20 Sept



Urban ventilation

how often does the wind speed exceed 2 m/s (cool breeze) annual average



Conclusions:

- The river has enormous ventilation potentialt hat is currently not always exploited. People could find a lot of cooling potential on or directly along the river.
- Open streets with few obstructions (such as trees) and a south-west (or similar) orientation could act as ventilation axes in the city, letting the wind from the river or another cool/windy spot enter the warmer urban fabric. A street with a lot of vegetation, such as the Heemraadsingel, seems unsuitable for this purpose.
- Places with a lot of wind nuisance, like many of the high-rise areas, also have a lot of urban ventilation. These two themes are opposed to each other; a site-specific balance must be sought, based on the specific challenges of the place.
- There are many places in the city that turn deep red and thus have little ventilation potential. This is particularly true for the low-rise, high-density prewar neighbourhoods. 'Het Park' also colours red, but this is not problematic, since the large amount of greenery and shade and the absence of heat-retaining material compensate for the absence of wind.

It is interesting to compare the results with:

- Areas for staying, such as playgrounds and benches.
- Trees/ vegetation/ perceived temperature/ shade map: this helps you find out which places have the strongest heat problems, because there is, for example, little shade, little greenery, a lot of heat-absorbing material and little wind. In contrast, places with little shade but a lot of wind may be less of a problem than currently thought.

Ventilation potential on a hot day: July 1st 2015

July 1st 2015 was a tropical day when the maximum temperature in Rotterdam rose to 34 ºC and the wind predominantly came from an easterly direction. It is a hot day that occurs about once every 5.5 years in today's climate. This day is used as a reference for the standardised heat map about perceived temperature (PET map) that maps the local perceived temperature on a hot summer day for any location in the Netherlands. The perceived temperature depends on weather factors (including wind), the environment and personal factors. It is also a good indicator of heat stress. The map on the right shows the average wind speed on July 1st 2015.

Conclusions:

- Even on a very hot day with relatively little wind, buildings visibly influence wind movements. In the neighbourhood of Charlois, for example, there is hardly any wind, except around a residential tower, where the average wind speed exceeds 3 m/s. Another well-known example is the New Luxor Theatre, where it always seems to be windy, even on a windless day. That feeling turns out to be true.
- On much of the usually windy river, relatively low wind speeds are calculated for July 1st 2015 . Due to the orientation of the New Maas, (south) east winds turn out to be unfavourable for urban ventilation.

Urban ventilation: ventilating particulate matter out of the street

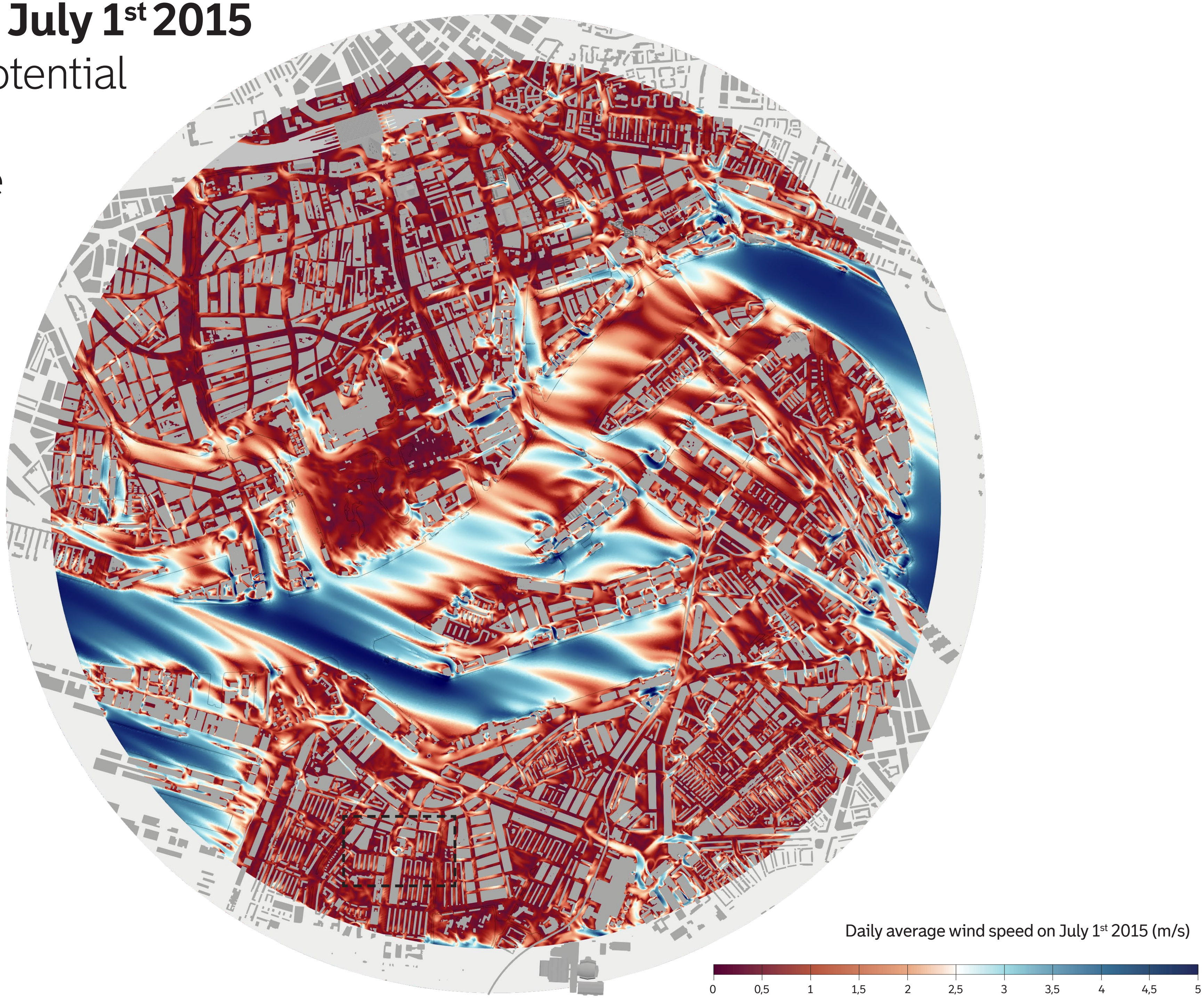
The map of urban ventilation (what percentage of the time the wind speed exceeds 2 m/s) is not just relevant for heat stress, but also for air quality. A breeze can blow particulate matter out of the street. In streets with little urban ventilation, particulate matter is more likely to accumulate to unhealthy or even dangerous concentrations. In streets with a lot of urban ventilation, this risk is smaller.

It is interesting to compare the results with:

- DCMR air quality map: the combination of poor air quality and low urban ventilation can be problematic.
- Mobility data: where are frequent traffic jams and where is traffic intensity high? Those places produce a lot of emissions. If this goes hand in hand with little urban ventilation, air pollution is trapped in the street for longer periods of time. It might be wise to prioritise these streets when it comes to reducing traffic. An example is the Mathenesserlaan, where there seems to be little ventilation while the traffic intensity is high. The combination of high traffic intensities and many trees with large crowns (blocking ventilation) can worsen the accumulation of particulate matter.

Wind speed July 1st 2015

ventilation potential
on a hot day
daily average



Particulate matter dispersion

An additional test of particulate matter dispersion was done for a number of locations in the city. Particulate matter sources were placed in the model, injecting particles from a given point. How these particulate matter particles will disperse under the influence of wind currents was then simulated for each wind direction. At each point in the model, the particle concentration can be determined and visualised.

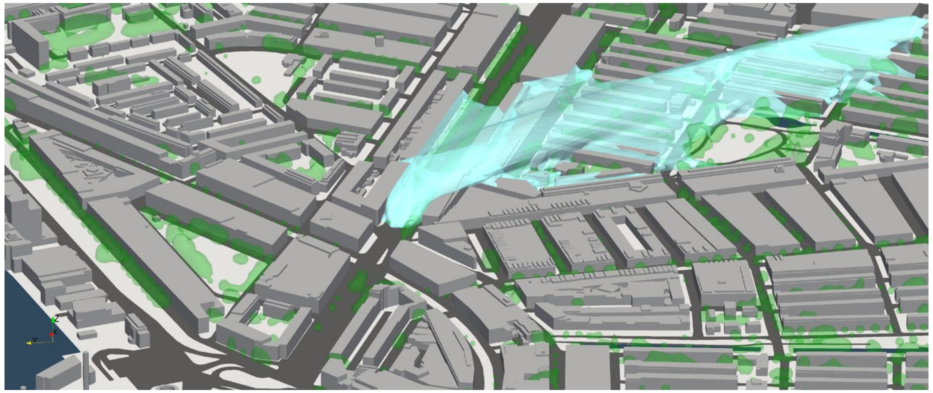
In the visualisations, the Pleinweg in the South of Rotterdam is shown. The images show the 3D contours of the particle concentration at different wind directions, both with leaf-bearing and leafless vegetation. This provides insight into the influence of buildings and vegetation on the dispersion of particulate matter in the city (from a given source).

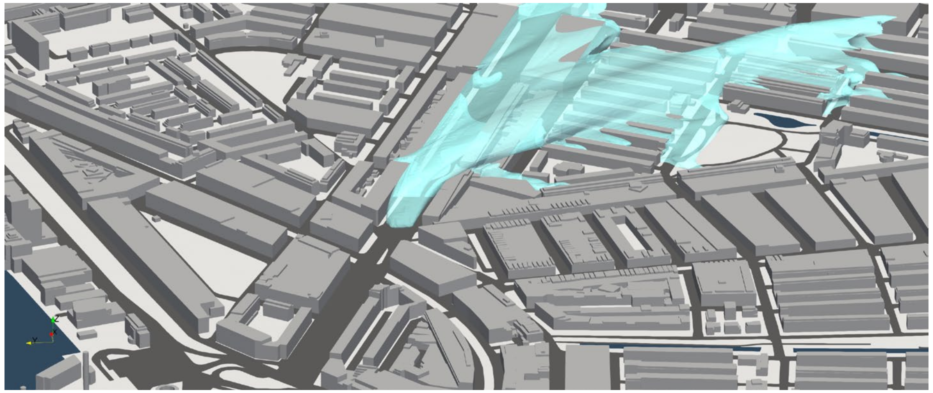
Conclusions:

- Wind-driven dispersion of particulate matter is strongly related to the prevailing wind direction and the environment of the pollution source. Not only do buildings form a barrier to particle dispersion, but also leaf-bearing trees. The visualisations show some examples where the 'cloud' reaches less far when leaf-bearing trees are included in the model: although long-distance particle dispersion is inhibited, in those cases the pollutant will linger longer around the source and have a higher local concentration.

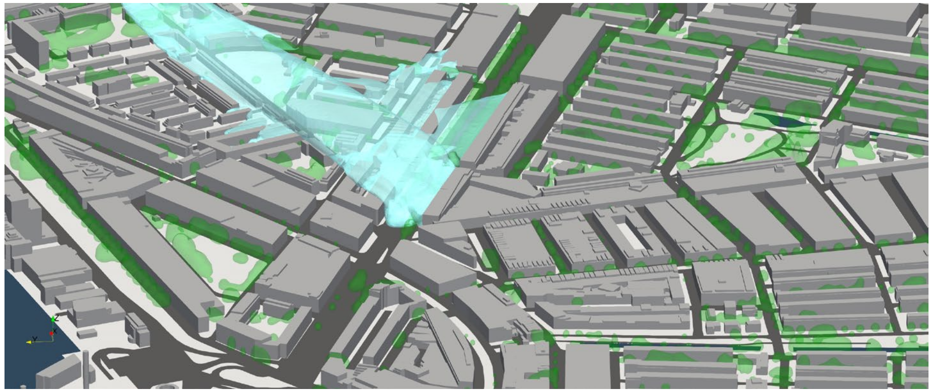
Urban ventilation summarised:

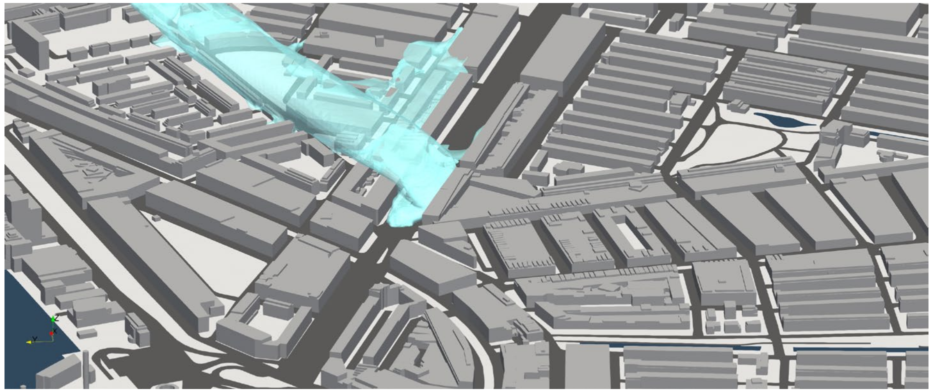
- Mapping urban ventilation provides many interesting insights for the topics of heat stress and air quality!
- Sites with little wind nuisance often also have (too) little ventilation potential. A site-specific balance must be sought.
- There are many places in the city with (very) little ventilation potential, especially the low-rise, high-density prewar neighbourhoods.
- Even on a very hot day with relatively little wind, buildings influence wind movements. Smart design can help use wind to mitigate heat stress during extreme days.
- Not only buildings, but also trees can hinder urban ventilation.
- Shade, greenery, materials and wind can compensate for each other or complement each other in terms of heat stress measures.
- The river and open streets facing southwest (or similar) have potential as ventilation axes.
- It is interesting to overlay this data with data on residence areas, shade, vegetation (heat), the DCMR air quality map and mobility data (air quality). The combination of high traffic and low ventilation likely results in poor air quality.





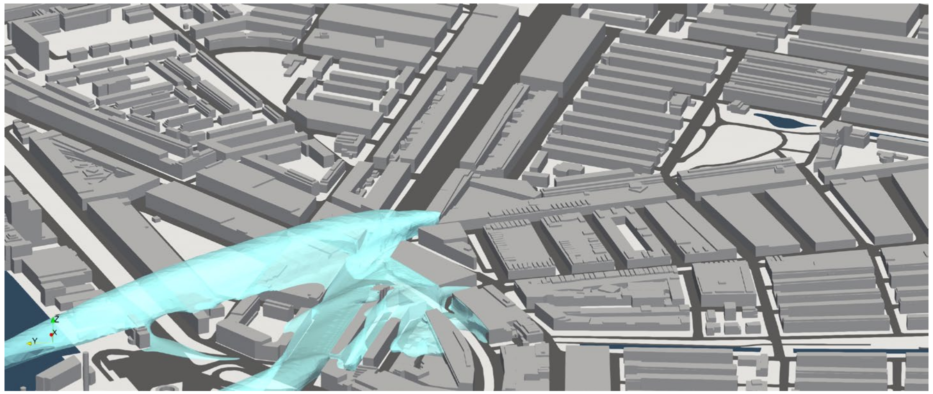
3D image of particulate matter dispersion at the Pleinweg, northwest wind





3D image of particulate matter dispersion at the Pleinweg, southwest wind

Particulate matter dispersion; the measured spots on the map



3D image of particulate matter dispersion at the Pleinweg, southeast wind

2.3 Wind energy on roofs.

Besides urban ventilation, wind also provides opportunities for energy generation. We already know a lot about this when it comes to large wind turbines outside urban areas. In this section, we explore the potential of inner-city rooftops for wind energy generation.

Wind energy potential at roof height

The map shows for each roof in the area how much energy you could generate if you put a small wind turbine on it. The roofs have different heights and the results are shown at 2 metres above each roof. The results are expressed in kWh/year/m^2, i.e.: how many kilowatts (kWh) can be generated in a year per m^2 of rotor area (the amount of space occupied by the rotating blades in terms of surface area). The wind speeds above the roof were converted to an energy yield based on the power curve of a generic wind turbine. This is type-dependent, so the exact results will change with a different type of wind turbine. In general, the stronger the wind, the more energy the turbine generates. But if the wind speed gets too high, it switches off to prevent overloading. As a result, the highest roofs (with generally the highest average wind speeds) do not necessarily have the highest output.

Conclusions:

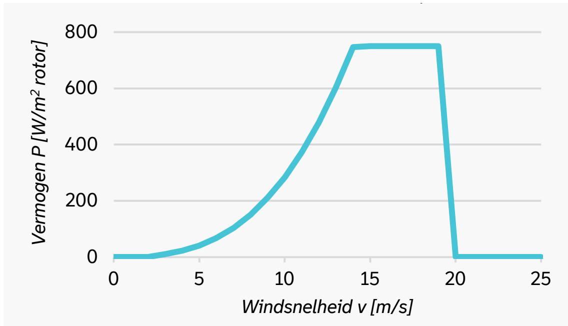
- This map provides new information: it clearly shows which locations are promising in terms of wind energy yield.
- The industrial area Waalhaven seems promising for rooftop wind energy. The incorporation there seems less objectionable than in the city centre.
- In addition, high, unprotected roofs seem promising, for instance, at the Kop van Zuid or the Lloydpier. At locations where tall buildings keep each other out of the wind (like in large parts of the city centre), there seem to be fewer opportunities. Many rooftops in the area do not seem very suitable for wind energy harvesting.
- Locations that seem promising may be dropped due to other issues, such as spatial integration or noise.

It is interesting to compare the results with:

- The city's rooftop programme (multifunctional rooftops).
- The map of solar energy potential on roofs: combining, complementing or choosing.

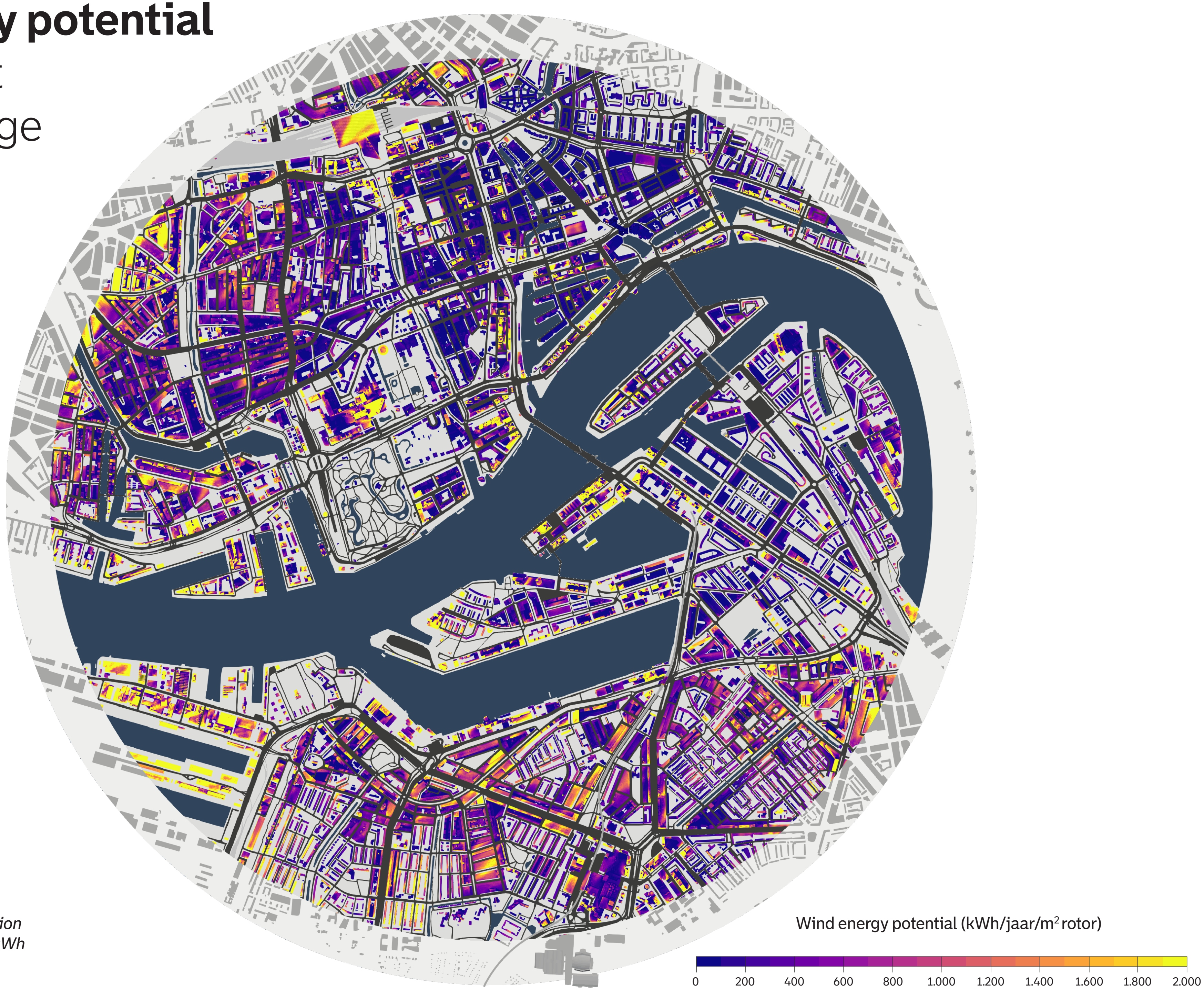
Wind energy on roofs summarized:

- The highest roofs do not necessarily have the highest yield: at too high wind speeds, the turbine shuts off, and in the centre, the towers keep each other out of the wind.
- The Waalhaven seems promising; just like high, unprotected roofs, for example at Kop van Zuid or Lloydpier.
- Many rooftops in the area do not seem very suitable for wind energy harvesting.
- It will be interesting to combine this data with the rooftop programme and solar potential on rooftops.



Applied power curve wind turbine with maximum efficiency of 40% (Cp = 0.4)

Wind energy potential
at roof height
annual average



The average electricity consumption of a 3-person household is 3250 kWh per year (source: Nibud)

2.4 Storm.

And finally, there is also the presence of wind during extreme weather: a storm! Before we started this pilot, we did not have this topic in mind. During the process, we decided to see what would happen if we visualised a storm day, based on measurements of wind direction and wind speed on that specific day. This produced very interesting maps that sparked our imagination. It inspired us to think about the relationship between climate adaptation and wind. More frequently, extreme weather events will occur in the Netherlands, but what are their implications for urban safety? That is what we explore in this section.

Wind speeds during storm Eunice

KNMI speaks of a storm if the average wind speed equals wind force 9 for at least 1 hour, i.e. if an hourly average wind speed of 75 km/h or more is measured. In the Netherlands, storms occur a few times a year. Storms for which KNMI issues a code orange or red for wind gusts are given a name.

On 18 January 2022, storm Eunice raged through our country. There was a westerly to southwesterly wind with wind force 10 and wind gusts of up to 40 m/s (145 km/h) were measured. This is exceptional; Eunice is among the top 3 heaviest storms in the Netherlands since 1970 and was the deadliest since 2007. The map gives an impression of the wind speeds achieved during a storm similar to storm Eunice. The scale is capped at 20 m/s (72 km/h), but higher wind speeds are reached in several places (marked in yellow on the map).

Conclusions:

- During storm Eunice, the criterion for wind danger (15 m/s) was greatly exceeded in many places in the city (sometimes even above 20 m/s), mainly on the bridges, along the river and around tall buildings. During that day, people were being evacuated from the Erasmus Bridge by the police because they could not leave by themselves. In such cases, it might be wise if the municipality would block off certain places or advise people to avoid certain spots for safety reasons.

Milder storms: Ciara en Pia

Eunice was exceptional, but severe storms occur more often in Rotterdam. In 2020, for example, we had storm Ciara and in 2023 storm Pia (also causing high water levels and closure of the Maeslantkering). Storms of this strength currently occur almost annually and the frequency of extreme weather is increasing due to climate change.

Conclusions:

- The wind distress threshold is exceeded in many places even during annual storms.
- Which places are dangerous depends on the wind direction.
- It is possible to make predictions, by loading real-time wind forecast data (the expected wind direction and speed) into the model.

Storm summarized:

- During a storm, many places in the city are dangerous. Which ones depend on the wind direction.
- By combining this kind of study with real-time wind forecast data, it is possible to make predictions and e.g. block off dangerous spots during storm events.

Wind speed during storm

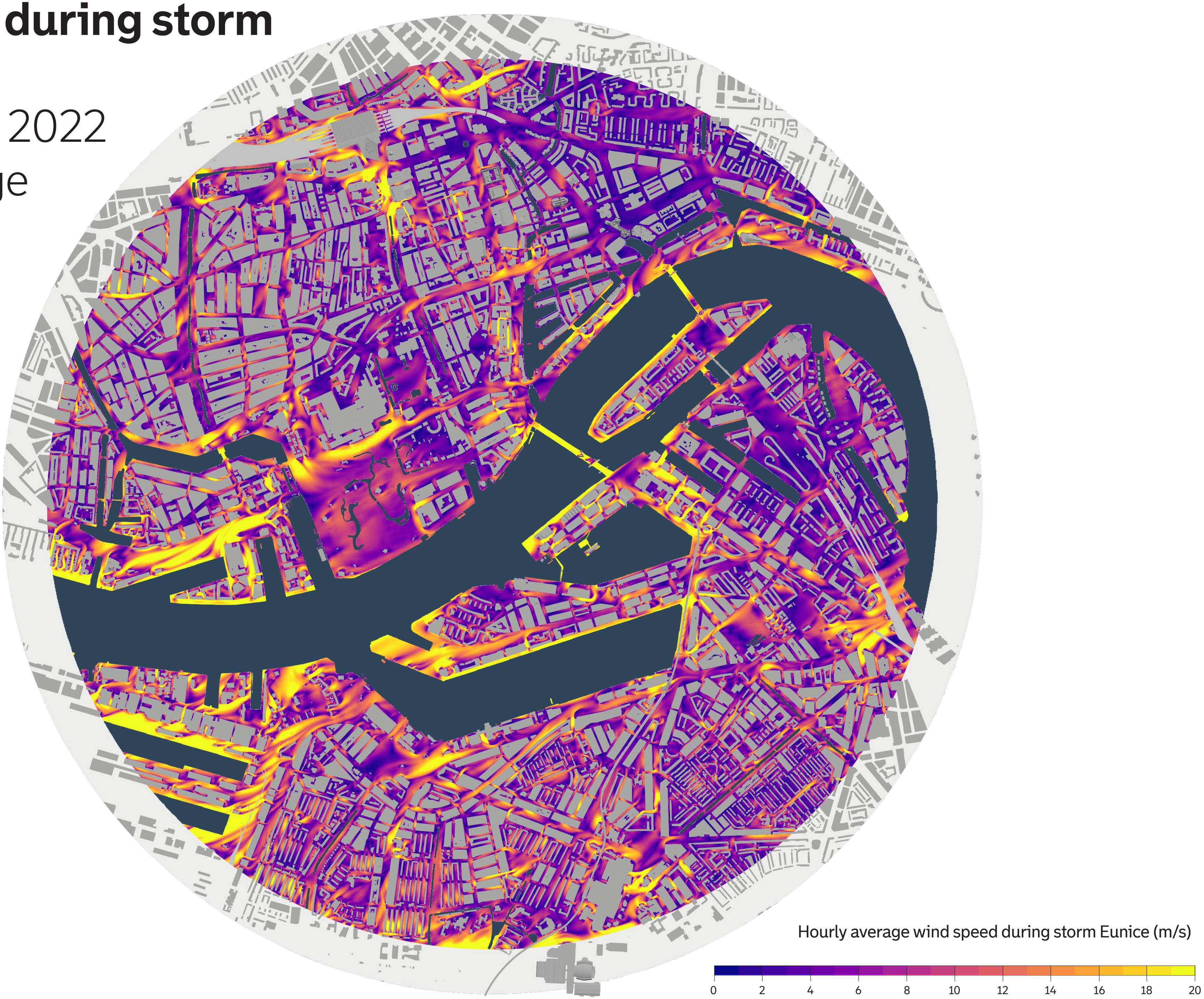
storm Eunice

February 18th 2022

hourly average

westerly wind

wind force 10



Wind speed during storm

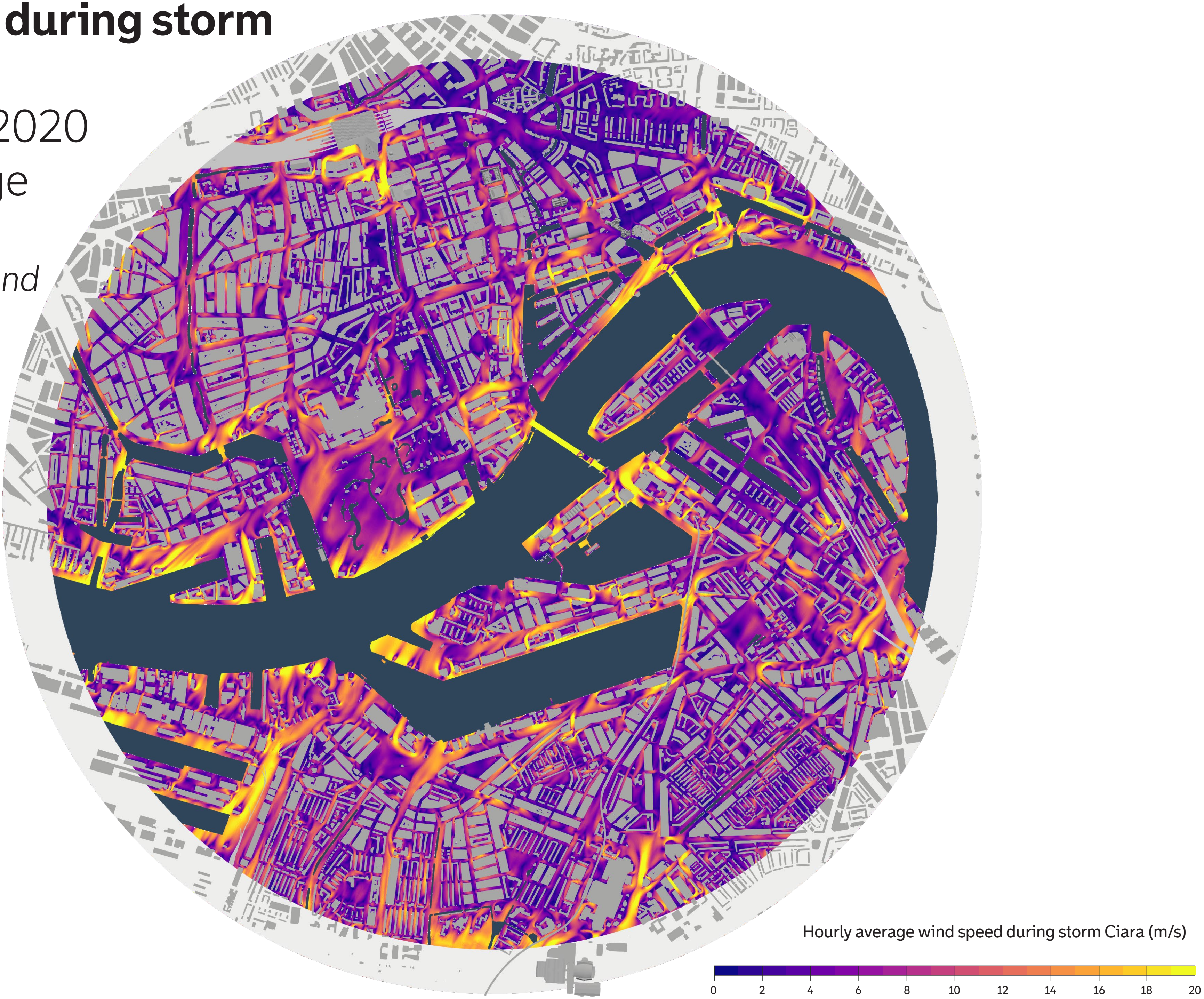
storm Ciara

February 9th 2020

hourly average

southwesterly wind

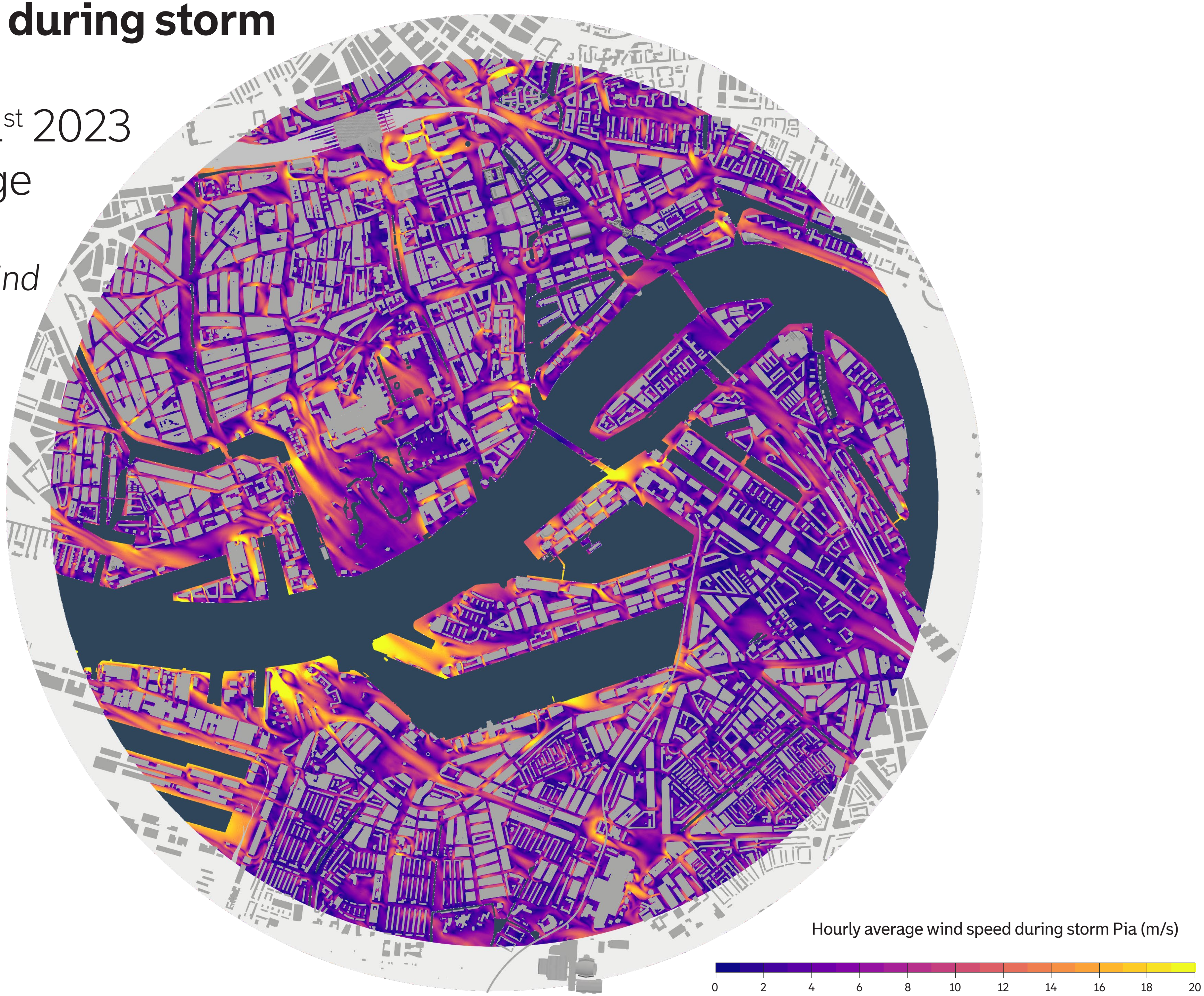
wind force 9



Wind speed during storm

storm Pia
December 21st 2023
hourly average

northwesterly wind
wind force 8



3. Conclusions.

The pilot Wind as an Opportunity has shown that the theme of wind offers way more possibilities than many people expected. It is impressive to see a wind study for such a large area for the first time. And adding new themes to the mix provides many new insights. The open, experimental nature of the pilot also worked out well; much more was explored and discovered than expected beforehand. The theme 'storm', for example, was not included in the initial proposal, but is now proving to be an important stimulus for thinking about linking wind to the urban climate adaptation agenda. Many people are impressed by the results, have learned new things and enthusiasm is growing to take this theme further. Of course, the question remains: what is the next step and how will this pilot influence our ways of working? The next page shows a summary of the conclusions per theme. But first some general issues are highlighted.

Finding the right balance: wind nuisance versus urban ventilation

An important insight is that the design guidelines for urban ventilation (against heat stress and air quality issues) and wind nuisance/distress are opposites in essence, so a balance must always be sought. You don't want wind nuisance and distress, but you do want a pleasant breeze in summer. This is an important but complex design challenge, the goal of which depends on the location in the city.

Look at it on an urban scale

The results clearly show that you need to look at wind on the urban scale first. Cleverly designing, for instance, building heights and their uniformity in the area, the placement of towers and set-backs and the orientation and widths of streets offers lots of opportunities. If wind is not taken into account on the scale of the urban design, it will probably be very hard to solve occurring problems at building or street level. Not only for new urban plans, but also for existing neighbourhoods, it is smart to think about wind on an urban scale.

Opportunities and next steps

The results are directly useful for making certain design and policy choices. In addition, they provide opportunities for possible follow-up steps. Some ideas from the brainstorm sessions for follow-up steps that the Municipality of Rotterdam and/or others could take (in addition to the conclusions per theme presented in the summary):

- Let the maps serve as examples of what you can get out of a wind study, in addition to the usual maps of wind nuisance and distress, for planned and new future studies, not only of high-rise areas but e.g. also of places with heat stress or air pollution.
- Extend this study to the whole city and/or calculate future scenarios.
- Compare results with measurement results from wind sensors in the city and/or with residents' perceptions.
- Looking not only at the desired wind climate in relation to use for people, but also for animals and plants.
- Looking at the maps at the neighbourhood level to extract spatial principles and starting points for different types of neighbourhoods. Different

principles and design guidelines may apply to the city centre than to post war neighbourhoods or garden cities. The task varies from place to place. For instance, some places have too much wind, others too much heat stress or air pollution. And this can also vary by season. Which measures effectively solve the occurring problems depend on the situation. More (design) research can be done on this. This would be useful both for improving the existing city and for new urban developments.

- Within the municipality, look for connections between wind and existing policy (city vision, college objectives, (inter)national etc.) and various departments/programmes (urban management, climate, urban planning, landscape, planting, safety, sustainability, environment, engineering, energy, roofs, data etc.).
- Technical: further investigate the impact on the results of calculating such a large area. And what lessons can be learned from this pilot for the revision of the Dutch norm NEN8100, which starts in 2025?
- Share the results widely and, together, extract even more than what has already been mentioned in this report.

Afterword

This report might set many people thinking, at municipalities, companies, universities and other interested parties. And that is exactly the intention. This pilot is meant to be a first step, the beginning of thinking about wind as an opportunity on a larger scale. The maps in the report show a lot of new information that was unknown before, so they can continue to provide new insights and opportunities for new connections. We therefore invite everyone to think along: what do you get out of this? What can you do with it? How can you use it in your work (or daily life)?

The municipality of Rotterdam sees the potential of this pilot. The wish exists to scale up the study to the entire city. Additionally, we are looking at how to embed the theme wind more broadly within the organisation. Hopefully, this will inspire other municipalities and organisations, nationally or even internationally, to get involved as well. This report will be widely shared, both internally and externally. So please forward it to others!

More research is needed before making concrete changes in policy and design. One example is additional confirmation of the reliability of the results. Of course, the study was conducted carefully and according to the best practice guidelines, but the application in a larger area is experimental and new. No rights can therefore be derived from the results of this report. However, many new insights can be gained from the maps as they are presented now. Therefore, we warmly invite you to use the results for discussion and as inspiration to include the opportunities of wind in design and policy. Let's work together on wind as an opportunity!

Summary.

Introduction:

- Goal: healthy, safe and liveable cities.
- 'Urban air systems' have a lot of potential, which often remains underused.
- We already do many wind studies, but we get very little information from them; that is a waste of potential.
- For the first time, we are doing a study on a larger scale, including multiple districts and areas at the same time instead of separate buildings/urban developments.
- We brainstorm with a multidisciplinary group of experts about the opportunities and next steps.
- Many interesting and surprising insights emerge!

Introduction of the results:

- The simulations were made using CFD (Computational Fluid Dynamics).
- From one series of simulations you can make many different maps and images; which ones were determined during the brainstorm sessions.
- The wind rose used is based on the most recent meteorological dataset of the KNMI.
- Above the river the annual average wind speed is relatively high.

Wind nuisance and distress:

- Wind distress ('dangerous' according to NEN8100) hardly occurs in the area. 'Limited risk of wind distress' does occur, mostly along the river and/or around high-rise buildings.
- The largest part of the area has wind nuisance class A (the most windless). In a number of zones, much more wind nuisance occurs, mostly along the river and/or around high-rise buildings. The bridges, the Kop van Zuid, the area around the central station and the Lloydpier stand out.
- It is interesting to overlap this data with data on, among other things, building heights, places to sit, waste containers and vegetation.
- It is possible and useful to look at the summer and winter seasons separately, because the use of public space in the Netherlands varies greatly per season. On average, there is less wind in summer and more in winter time.
- The English method, Lawson, assesses wind nuisance and wind distress differently from the NEN8100. The results seem too positive compared to our experiences in reality.

Urban ventilation– heat stress and air quality:

- Mapping urban ventilation provides many interesting insights for the topics of heat stress and air quality!
- Sites with little wind nuisance often also have (too) little ventilation potential. A site-specific balance must be sought.
- There are many places in the city with (very) little ventilation potential, especially the low-rise, high-density prewar neighbourhoods.
- Even on a very hot day with relatively little wind, buildings influence wind movements. Smart design can help use wind to mitigate heat stress during extreme days.
- Not only buildings, but also trees can hinder urban ventilation.
- Shade, greenery, materials and wind can compensate for each other or complement each other in terms of heat stress measures.
- The river and open streets facing southwest (or similar) have potential as ventilation axes.
- It is interesting to overlay this data with data on residence areas, shade, vegetation (heat), the DCMR air quality map and mobility data (air quality). The combination of high traffic and low ventilation likely results in poor air quality.

Wind energy on roofs:

- The highest roofs do not necessarily have the highest yield: at too high wind speeds, the turbine shuts off, and in the centre, the towers keep each other out of the wind.
- The Waalhaven seems promising; just like high, unprotected roofs, for example at Kop van Zuid or Lloydpier.
- Many rooftops in the area do not seem very suitable for wind energy harvesting.
- It will be interesting to combine this data with the rooftop programme and solar potential on rooftops.

Storm:

- During a storm, many places in the city are dangerous. Which ones depend on the wind direction.
- By combining this kind of study with real-time wind forecast data, it is possible to make predictions and e.g. block off dangerous spots during storm events.

Let's work together on wind as an opportunity!

4. Technical explanation.

How was the simulation executed exactly? How have the results been processed? And which technical 'challenges' did we run into duringthe process? This chapter explains the technical side of the pilot. This is especially interesting for people who want to understand how we got to these results, people who want to repeat parts of the study (for instance, for other areas), or who would like to find inspiration for follow-up research. In the table on the page next to this, the technical specifications and settings are summarized.

3D-model

The geometry of the model has been created based on a combination of open geodata, including BRT TOP10NL, 3DBAG, AHN and Rotterdam 3D. The model includes a circular core area with a radius of 2,500 m, in which all existing buildings and buildings currently being built, or that have received a building permit before april 2024 are being taken into account. Outside of the core area, a 250 m wide ring has been added in which the building volumes are modeled as simplified extrusions from their circumference on the terrain. This explicitly modeled area is placed in a cylindrical domain having a diameter of 8,000 m and a height of 800 m. The terrain roughness of the ring without explicitly modeled buildings (the outer ring of the 3D model) has been made in correspondence with the actual situation according to the Dutch NPR6097:2006.

Computational mesh

The computational mesh is created by dividing the air volume inside the aforementioned domain into a large number of volumetric cells. During this project, the computational mesh has been created semi-automatically using snappyHexMesh. In total, the computational mesh has over 583 million cells, with edge lengths of these cells varying between 0.25 m up to 4 m inside the core area. The local dimensions of the cells depend on the details of the geometry. Towards the edge of the domain, the edge lengths of the cells increase up to 64 m. From the terrain surface and the walls of the buildings, five prismatic layers of an-isotropic refinement have been extruded. This operation results in an increased resolution in the normal direction of the relevant wall boundary compared to the tangential directions. These layers improve the computation of the velocity gradient in the (atmospheric) boundary layer.

Vegetation

Vegetation has a relevant influence on the wind climate and therefore has been included in the core area. This influence, however, changes during the year, depending on the season and the type of vegetation. At the same time, the wind conditions change during the year. To have as realistic a wind climate result as possible, two sets of simulations have been made for the entire year: One set considers the vegetation with leaves (representing the summer situation) and the other set considers leafless vegetation (representing the winter conditions). The average of both results has been determined to get a representative result for the full year wind climate.

The wind statistics

To visualise the wind climate, 12 wind directions have been simulated to represent the complete wind rose. The wind statistics have been created from the DOWA (Dutch Offshore Wind Atlas) data set of the KNMI using wind measurements in the period 2008-2017. This data set has a resolution of 2.5 km. Due to the large coverage of the computational domain, the

Technical specifications and settings.

3D-model	
Size of the modeled area	Buildings within a radius of 2,750 m (from the centre of the domain)
Core area	Circular with a radius of 2,500 m, including existing buildings and all new buildings being constructed or having been granted a building permit before april 2024, including vegetation
Surrounding area	Ring of 250 m, containing simplified building volumes, no vegetation
Domain size	Cylindrical with 4,000 m radius and a height of 800 m
Blockage ratio	3% maximum
Modeled vegetation	Tree clusters: porous zone
Wind directions considered	2 x 12 (full circle with steps of 30 degrees, full and leafless vegetation)
Configurations considered	Single configuration
Computational set-up	
Software	■ FVM (Finite Volume Method) ☐ FEM (Finite Element Method) ☐ Other Software:: OpenFOAM Version: v2312
General	■ three-dimensional ■ steady-state ■ isothermal ■ passive scalars ☐ two-dimensional ☐ transient ☐ non-isothermal ☐ active scalars Other: --
Computational mesh	Hybrid unstructured: hexcore mesh using hexahedrons and polyhedrons with an-isotropic refinement near walls Mesh: 583,381,118 volumes
Turbulence model	SST k-ω
Convective discretisation schemes	Velocity components: linearUpwindV cellLimited leastSquares 1 Turbulent variables: limitedLinear 1 Scalar variables: linearUpwind cellLimited leastSquares 1

Boundary conditions			
Inflow profile	Logarithmic atmosferic boundary layer with local roughness in the surroundings based on NPR6097:2006		
Outlet	Pressure outlet		
Top/side walls	Slip walls		
Floor/ground	No slip/rough wall		
Other walls	No slip, rough or smooth walls		
Data processing			
RD-coordinates of the location	X: 92590, Y: 435697 (centre of the domain)		
Applied criteria	V_{DR} [m/s]	quality classe	Probability of exceedance $p\ (V_{LOK} > V_{DR;H})$ [%]
For wind distress (NEN8100)			
Limited risk	15,0	n/a	$0{,}05 < p < 0{,}30$
Dangerous	15,0	n/a	$p \geq 0{,}30$
For pedestrian wind comfort (NEN8100)			
Business walking	5,0	A, B, C	$p < 10$
Walking leisurely	5,0	A, B	$p < 5$
Sitting	5,0	A	$p < 2{,}5$
For pedestrian wind comfort (Lawson LDDC)			
Walking	8,0	leisurely walking	$p \leq 5$
Standing	6,0	standing	$p \leq 5$
Sitting	4,0	occasional sitting	$p \leq 5$
Results shown	Wind distress: contours and classifications Pedestrian wind comfort: contours and classifications according to NEN8100:2006 (yearly averaged and per season) and Lawson LDDC Wind velocity: Continuous scale, hourly averaged in general, daily average on july 1st 2015 (thermal discomfort) and highest hourly average during selected storms)		
Remarks and conclusions	--		

wind rose has been composed from relevant wind statistics of multiple locations: 12 sampling locations at the edge of the domain were selected (one sampling location per wind direction). The resulting wind rose is visualized in Chapter 2.

Methodology

For each wind direction considered, a resulting velocity field is determined. This results in a wind speed ratio (acceleration factor) compared to the supplied reference wind speed. Upon combination of the wind speed ration with the wind statistics, an exceedance probability for each wind speed can be determined at each location. This exceedance probability can then be compared to a requested quality classification to determine if the wind climate can be comfortable.

Software

The calculations have been executed using OpenFOAM v2312, a software suite meant to solve problems in continuum mechanics en thermodynamics. This project uses the "simpleFoam" solver, which solves the Reynolds-Averaged Navier-Stokes (RANS) equations for incompressible fluids, considering turbulence. The turbulence model used is the SST k-ω model.

Assumptions and boundary conditions

The simulations use a reference wind velocity of 5 m/s at a reference height of 60 m. A logarithmic atmospheric boundary layer profile is considered over the entire domain height. It is assumed that this atmospheric boundary layer has a velocity profile according to equations 4.1 and 4.2. In these equations, Un is the horizontal wind velocity, z is the height above the terrain, and z0 is a roughness length. This roughness length represents the roughness of the terrain and varies with the land use. The constant κ is the von Kármán constant, taken as 0.41. This is an empirical constant related to the modeling of boundary layers. The turbulent variables k and ω also follow a prescribed profile, as shown in equations 4.3 and 4.4. The model constant Cμ has a value of 0,09. This model constant has also been empirically determined in the development of the turbulence model used (SST k-ω).

Computational time

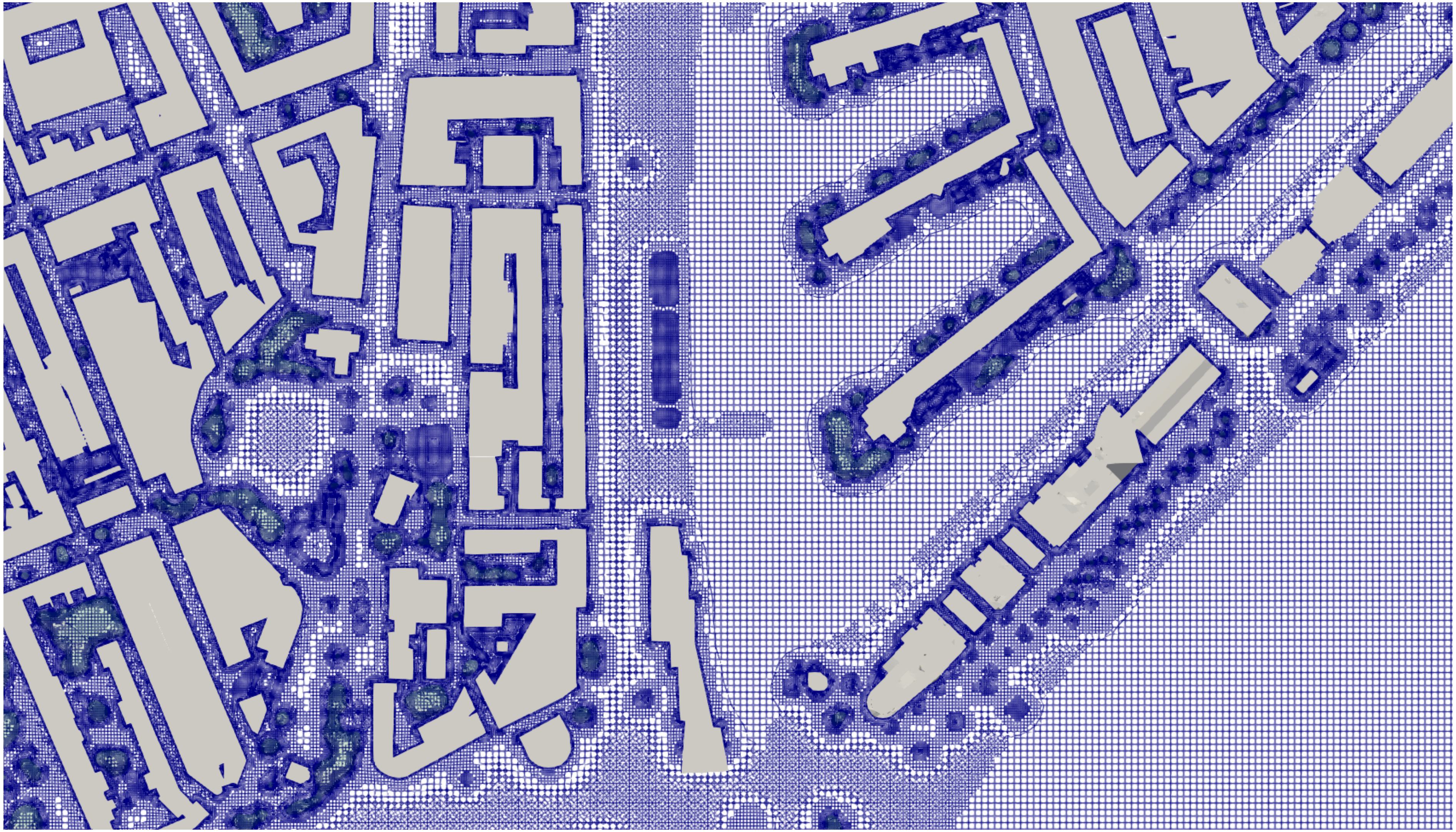
The computation mesh was created semi-automatically in 21.5 hours using 1024 CPU cores. The simulations took on average 4.75 hours per wind direction using 1536 CPU cores. For the post-processing of the simulations, two computers with a total of 1.25 TB of RAM memory were used.

$$U_n(z) = \left(\frac{U^*}{\kappa}\right) \ln\left(\frac{z + z_0}{z_0}\right) \tag{4.1}$$

$$U^*(z_0, U_{ref}, z_{ref}) = \frac{\kappa \cdot U_{ref}}{\ln\left(\frac{z_{ref}+z_0}{z_0}\right)} \tag{4.2}$$

$$k(z) = \frac{U^{*2}}{\sqrt{C_\mu}} \tag{4.3}$$

$$\omega(z) = \frac{U^*}{\kappa\left(z - z_{ground} - z_0\right)\sqrt{c_\mu}} \tag{4.4}$$

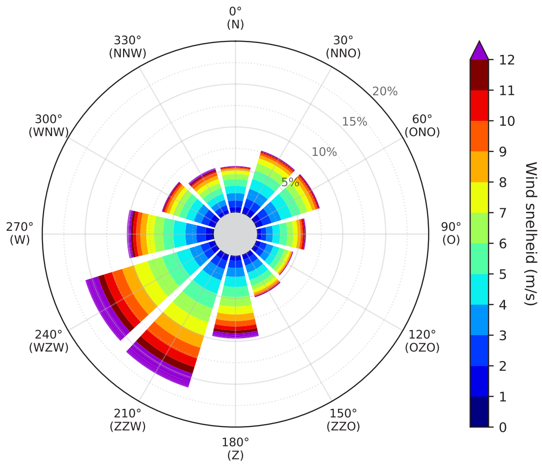


Visualisation of the computational mesh; slice at 10 m height; the computational cells become smaller when closing in on the core area (pedestrian height, buildings or vegetation)

5. Attachments.

Wind nuisance and wind distress according to NEN8100 with old data

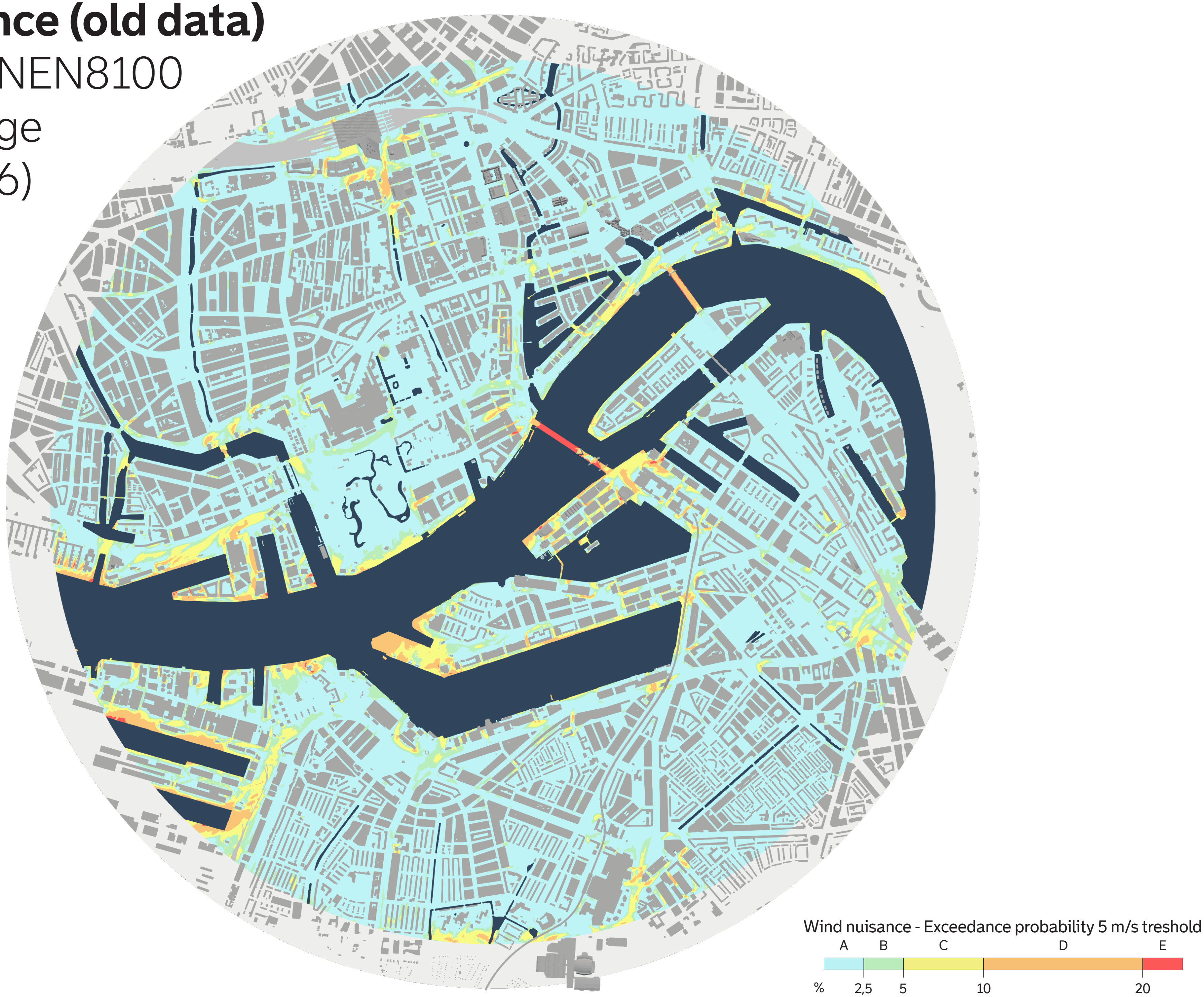
The results of the themes wind nuisance and distress according to NEN8100 and with the old KNMI dataset that is currently used in wind studies in the Netherlands can be seen here.



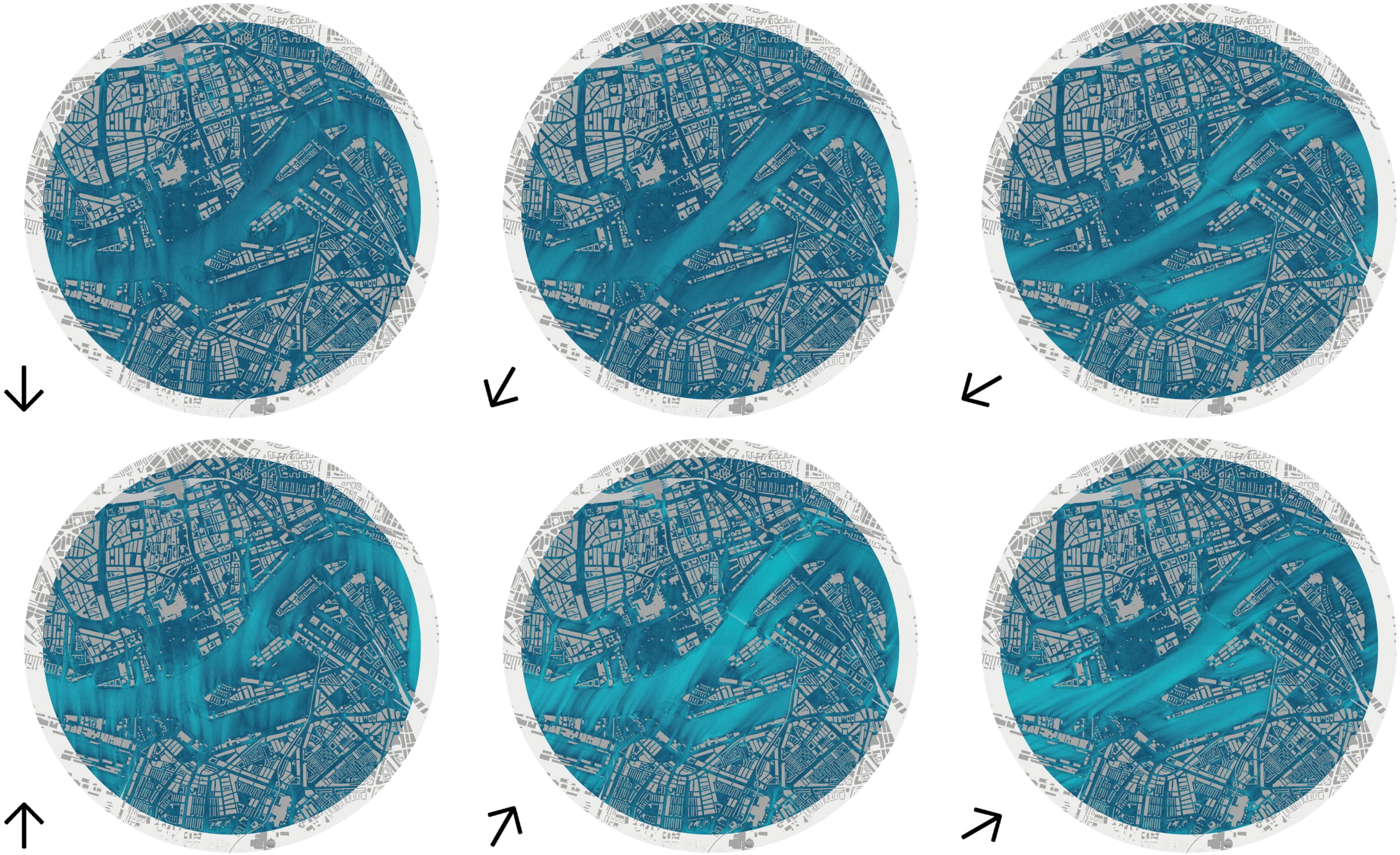
Wind rose as prescribed in NEN8100, with old meteorological data from 1963-2002 (NPR6097)

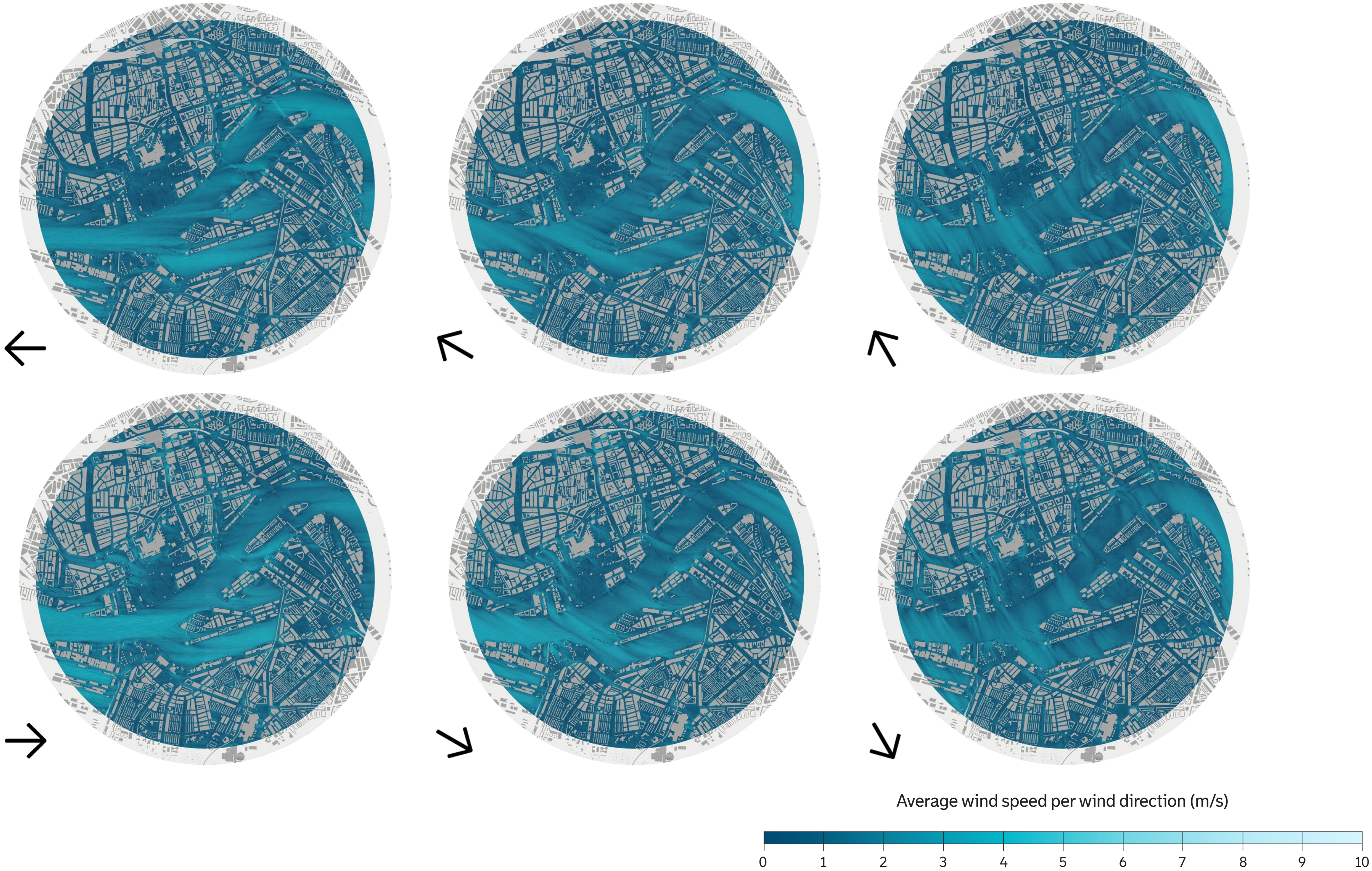
Wind distress (old data)
according to NEN8100
annual average
(legend pp. 14)

Wind nuisance (old data)
according to NEN8100
annual average
(legend pp. 16)



Wind distribution in different wind directions




Average wind speed per wind direction (m/s)
0
1
2
3
4
5
6
7
8
9
10