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Analysis of local climate effects for Martineåsen development project in Larvik

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Thank you very much, everyone!

Sincerely,
Maria Shunina

Contents

List of Figures

List of Tables

Abstract

The goal of this thesis is to perform analysis of local climate effects for Martineåsen development project in Larvik. The Norwegian regulatory acts place a strict requirements on outdoor areas comfort criteria and thus for the purpose of said development project, strict adherence to these acts is necessary. The outdoor comfort in cold climate is mostly governed by wind, and thus study of local climate effects in Martineåsen is needed, to evaluate the impact of construction work and local topography influence on the local wind effects. The first part of the thesis investigates general climatic conditions in Norway and Larvik, in particular, fluid mechanics, wind generation, the impact of wind effects on buildings and their components and comfort criteria on order to build a solid theoretical understanding of these effects and how they will translate to local conditions at Martineåsen development area. Second part of the thesis is concerned with CFD simulations of Martineåsen project area. The results show that removal of the forest at the hills, located in the general direction of prevailing wind direction will increase local wind effects at the site. Therefore, some alterations to building locations have been done to counter this increase. Results have shown that new configuration performs better than the original one and it is recommended to analyze the effects of different building configurations further.

1. Introduction

1.1 Background

The local municipality is responsible for planning and usage of the land in Norway in addition to ensuring strict adherence of said plans to building codes and standards is the Technical Regulations under the Norwegian Planning and Building Act (NPBA). These regulations have been in power since 1997. The general design requirements for outdoor activity areas are governed by human comfort criteria and safety issues based on the section 11-1 of NPBA. The design requirements are functionality requirements, depending on type activity and any further applications, if at all. The Norwegian building regulations require that all outdoor activity areas in general must be planned and developed in order to fulfil the given functionality requirements. Outdoor comfort in northern regions is mainly governed by wind conditions and therefore the outdoor activity areas must be sufficient shielded against its effects. Design, planning and development of wind shielding measures and outdoor areas sheltering is often referred to as wind control.

Favorable site selection is the basis for all traditional settlements. Throughout the history, people carefully selected sites that were naturally sheltered or least exposed to strong winds and blowing snow. Traditional villages in windy parts of Norway were always located in naturally sheltered zones. Now, most of the naturally sheltered locations for buildings are occupied, thus leaving more exposed sites as main options.

Larvik municipal is developing green areas in Martineåsen for residential and other purposes. This includes clearing of forest which will create wind exposed zones in a rather hilly terrain. For the land planning, it is therefore important to analyze the local effects of clearing out the local vegetation for further development in settlement's infrastructure. In particular, the sections of the highest hills may be very exposed to wind.

1.2 Statement of the Problem

This master thesis includes performing an analysis of local climate effects for development of Martineåsen project area in Larvik. The analysis will focus on wind and wind related effects on the outdoor environment. The analysis should include an analysis of local climatic conditions and their effects and relate to the ongoing municipal land planning process directed by guidelines given by the Larvik municipal project group.

1.3 Project Aim and Objective

The master thesis has the following goals and objectives:

- Perform analysis of local climate effects for Martineåsen development project in Larvik.
- Achieve better understanding and knowledge about wind conditions in outdoor areas in Larvik.
- Analyze the effects of clearing forest for land usage purposes at Martineåsen project ares
- Achieve better understanding and knowledge about outdoor comfort criteria and sheltering at the project site.
- Suggestions of wind shielding concepts for outdoor activity areas at Martineåsen.

2. Theory

2.1 Climate in Norway

Before construction can begin, it is important to analysis climatic and weather conditions for a given area. The weather describes the state of the atmosphere with respect to wind, temperature, cloudiness, moisture content in the air, pressure for a given area over a short period of time. The climate describes the typical weather conditions for the area for a long period. Norway is a sort of "stretched" country located in Northern Europe and one of Europe's most mountainous countries. The landscape features will have an effect on the weather conditions such as wind, precipitation and temperature. Although parts of the country are located north of the Arctic Circle, Norway has a much milder climate than typical Arctic regions, due to effects of warm ocean currents near the shores of Northern Norway.

Collection of climate data and information about the topography provides a better understanding of the area. According to W.P. Köppen empirical climate classification, which is one the most widely used climate classification systems, the climate in Norway can be classified into groups, as given in Table 1.

Köppen-Geiger climate classification	Characteristic
ET (Tundra climate)	Mild tundra climate.All 12 months of the year with average temperatures between 0 °C and 10 °C.
Dfc (Subarctic climate)	Coldest month averaging below 0 °C and 1–3 months averaging above 10 °C. No significant precipitation difference between seasons.
Dfb (Warm-summer humid continental climate)	Coldest month averaging below 0 °C, all months with average temperatures below 22 °C and at least four months averaging above 10 °C. No significant precipitation difference between seasons.
Dsc (Dry-summer subarctic climate)	Coldest month averaging below 0 °C and 1–3 months averaging above 10 °C. At least three times as much precipitation in the wettest month of winter as in the driest month of summer, and driest month of summer receives less than 30 mm.
Dsb (Warm-summer mediterranean continental)	Coldest month averaging below 0 °C, all months with average temperatures below 22 °C, and at least four months averaging above 10 °C. At least three times as much precipitation in the wettest month of winter as in the driest month of summer, and driest month of summer receives less than 30 mm.
Cfc (Subpolar oceanic)	Coldest month averaging above 0 °C and 1–3 months averaging above 10 °C. No significant precipitation difference between seasons.
Cfb (Oceanic)	Coldest month averaging above 0 °C, all months with average temperatures below 22 °C, and at least four months averaging above 10 °C. No significant precipitation difference between seasons.
Csc (Cold-summer mediterranean)	Coldest month averaging above 0 °C and 1–3 months averaging above 10 °C. At least three times as much precipitation in the wettest month of winter as in the driest month of summer, and driest month of summer receives less than 30 mm.
Csb (Warm-summer mediterranean)	Coldest month averaging above 0 °C, all months with average temperatures below 22 °C, and at least four months averaging above 10 °C. At least three times as much precipitation in the wettest month of winter as in the driest month of summer, and driest month of summer receives less than 30 mm.

Table 1. Köppen-Geiger climate classification of climate in Norway (classification K.-G. c., 2017)

Norway has many different climates, but is mostly dominated by Subarctic (Dfc) Köppen-Geiger type. Figure 1 shows a map of Köppen-Geiger climate types for climatic conditions in Norway.

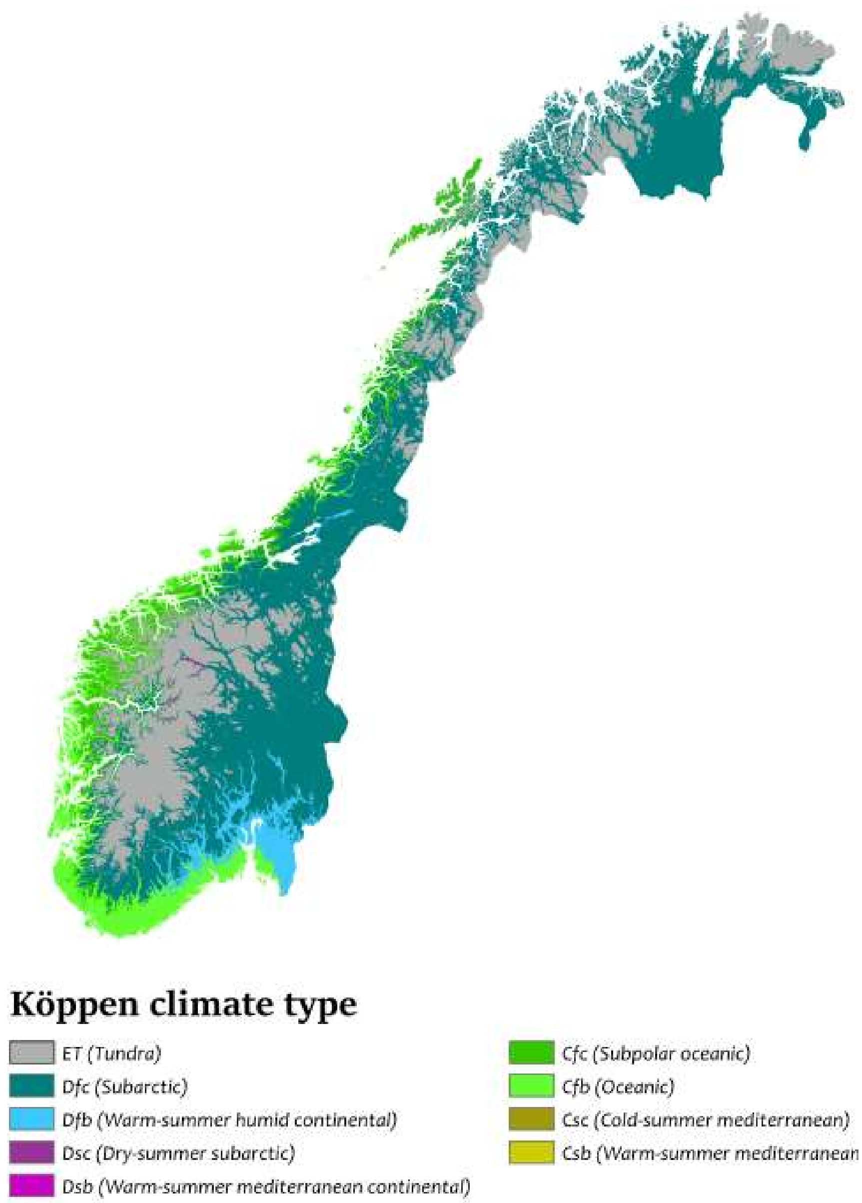

Figure 1. Map of Köppen-Geiger climate classification of climate in Norway (classification K.-G. c., 2017)

2.2 Local climate

Local climate (or mesoclimate) describe those climates, which influence rather small geographical areas with fairly uniform natural conditions, for example, a particular wooded area, seashore, part of a river valley, mountain range, small city, or urban district. It is intermediate in scale between the macroclimate and the microclimate. The local climate is largely determined by the type of surface in the given region, its topography, soil, vegetation, buildings present etc. These features are most pronounced in the lower layer of the atmosphere, up to about several hundred meters, but they gradually level out with increasing altitude. The local climate is usually characterized by statistical conclusions, drawn from long-term observations made by meteorological stations in the region. Any construction project, based on its size, will be affected by both microclimate, if the project in question is confined to a small area, and local climate, if it is larger in size (Utaaker, 1991).

Climate	Horizontal Extension	Vertical Extension
Microclimate	1 cm – 1000 m	1 cm – 10 m
Local Climate	100 m – 20 km	10 cm – 1 km
Mesoclimate	(10 – 200 km)	(1 m – 6 km)
Macro Climate	> 200 km	1 m – 50 km

Table 2. Climate parameters in different scale (Utaaker, 1991)

Macroclimate analysis gives more general information about accumulated seasonal differences in temperature, wind speeds and wind directions. The macroclimate around a building cannot be affected by any design changes, however the building design can be developed with a knowledge of the macroclimate in which the building is located. Microclimate analysis gives information about climate in immediate surroundings of buildings. The building site may have a significant number of different microclimates caused by the presence of hills valleys, slopes, streams, other buildings, etc. The presence and location of any neighboring trees and buildings affects exposure to the sun and wind patterns. (Utaaker, 1991)

2.3 Climate in Larvik

Climate in Larvik is characterized by equable climates with few extremes of temperature and ample precipitation in all months. Larvik is located poleward of the Mediterranean climate region in the southern part of Scandinavian penisula, with latitude 59.053°N and longitude 10.0272°E. According to the Köppen Climate Classification, the climate in Larvik is classified as Cfb climate, also known as temperate oceanic climate. Temperate oceanic climates are located beyond the farthest poleward extent of the subtropical anticyclone, and they experience the mid-latitude westerlies and traveling frontal cyclones all year. Temperatures in the winter tend to be mild, while summer temperatures are moderate. The average temperature for the year in Larvik is 6.3°C. The warmest month, on average, is July, with an average temperature of 16.6°. The coolest month on average is February, with an average temperature of -3.2°C.
Precipitation totals vary somewhat throughout the year in response to the changing location and intensity of these travelling storm cells. Many areas have rainfall more than 150 days per year, although the precipitation is often of low intensity. Fog is common in autumn and winter, but thunderstorms are infrequent. Strong gales with high winds may be encountered in winter. The average amount of precipitation for the year in Larvik is 738 mm. The month with the most precipitation on average is October with 89.0 mm of precipitation. The month with the least precipitation on average is April with an average of 38.0 mm. The summary information about average temperature and precipitation in Larvik, per month, is given in Tables 3 and 4, respectively.

Month	Jan	Feb	March	April	May	June	July	Aug	Sep	Oct	Nov	Dec

Temperature, ºC	-3,1	-3,2	0,3	4,5	10,3	14,8	16,6	15,3	11,5	7,4	2,2	-1,5

Table 3. The average temperature in Larvik (DNMI, 2017).

Month	**Jan**	**Feb**	**March**	**April**	**May**	**June**	**July**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Rainfall, mm	54	38	57	38	48	55	67	82	78	89	77	55

Table 4. The average amount of precipitation/ rainfall in Larvik (DNMI, 2017).

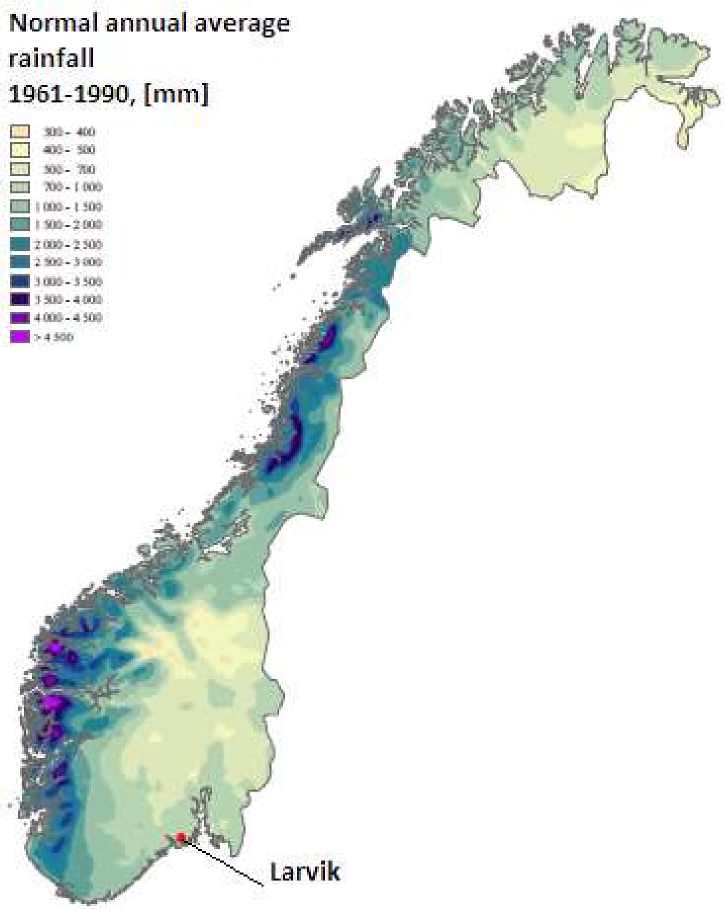

Figure 2. Overview of precipitation standards on a nationally and locally basis for Larvik (Meteorological institute, 2017)

2.4 Fluid mechanics

Both liquids and gases are fluids. The difference between fluids and solids is based on it molecular structure. A solid will retain its structure under the influence of applied forces while a fluid will deform when subjected to strain upon transverse load, also called shear stress. In another words - fluids cannot sustain shear stress, however it should not be mistaken with resistance of fluid to deformation. The fluid with zero resistance to shear stress is called an ideal or inviscid fluid, with the most known example being liquid helium at cryogenic temperature, which also exhibits superfluidity properties. Shear stress, defined as force per unit area is given in eq. 1 as follows:

$$\tau = \frac{F}{A}$$

Equation 1. Shear stress (Roylance, 2017)

Newton's law of viscosity is defined in eq.2 as:

$$\tau = \mu \frac{\partial u}{\partial y}$$

Equation 2. Newton's law of viscosity (Herman, 2017)

where $\tau = \frac{F}{A}$, μ is the absolute (dynamic) viscosity of the fluid, and $\frac{\partial u}{\partial y}$ is the derivative of shear deformation rate, also known as shear velocity, which yields the local shear velocity (rate of shearing strain) in the fluid.

When it comes to friction in fluid mechanics, the most important concept in is viscosity. Viscosity indicates how well a fluid can withstand gradual deformation under stress, and it also accounts for the shear force created in a fluid under movement and, in turn, fluid flow will depend on the properties of the fluid. It is natural that different fluids have different viscosity values, with so-called "thicker" fluids flowing at lower rate, due to having higher viscosity than so-called "thinner" fluids. (Munson, 2013). In addition, fluids can be divided into Newtonian and non-Newtonian fluids, according to the fluids' response under applied stress. Newtonian fluids follow Newton's law of viscosity, given in eq.2. In Newtonian fluid, the slope between shearing stress and rate of shearing strain is unity, i.e. any given change in shearing stress will be accompanied by linear change in rate of shearing strain, thus, the absolute viscosity μ is independent of stress. The same is not valid for non-Newtonian fluids, and their response to the applied stress can vary to a significant degree. Non-Newtonian fluids can be classified in the following way (Munson, 2013):

- Dilatant (shear-thickening) and pseudoplastic (shear-thinning) fluids, in which the apparent viscosity increases and decreases, respectively, with increase in stress.
- Rheopectic and thixotropic fluids, in which the apparent viscosity increases and decreases, respectively, with the duration of stress.
- Viscoelastic and viscoplastic fluids, which display a combination of viscous, elastic and plastic properties, respectively. Below a certain stress intensity, these fluids can behave like solids, with example being Bingham plastics, a class of viscoplastic fluids.

The apparent viscosity is defined as applied shear stress divided by shear rate in the fluid, and is given in eq. 3 as:

$$\eta = \frac{\tau}{\dot{\gamma}}$$

Equation 3. Apparent viscosity (Likavcan, 2017)

For Newtonian fluids the apparent viscosity is equal to the absolute viscosity μ.

Fluid flows due to the difference in pressure, external forces, gravity force, or a combination of those, and the flow can be bounded by solid surfaces. A fluid that flows close to a solid surface will match the velocity of said surface, due to viscous shearing forces. If the surface is at rest, the velocity of the fluid at the surface will be zero. This is known as "no-slip" condition. A fluid flow, bounded by from all sides is known as internal flow, an example being flow in the pipe. At the entrance of a pipe, the fluid will have a uniform velocity profile over the entire width of the pipe, also known as uniform or ideal flow. However, in some region, close to the pipe wall, the viscous effects cannot be ignored, and the "no-slip" condition will be enforced, which leads to the formation of distinct boundary layer in the fluid, close to the surface, while for the rest of the fluid the velocity changes, due to the viscous effects are negligible, thus separating the flow into two distinct regions: the boundary layer region and the core (irrotational) flow region (Munson, 2013). When the fluid enters the pipe, the thickness of the boundary layer gradually increases from zero until it reaches the pipe center, thus filling the entire pipe. This region from the entrance of the pipe to the point where the boundary layer covers the entire pipe is known as the hydrodynamic entrance region. In this region the velocity profile develops and thus the flow is called the hydrodynamically developing flow, as shown in fig. 3. Finally, after some point, the velocity profile is fully developed and it will remain constant throughout the rest of the pipe. This region is called the hydrodynamically fully developed region. However, it should not be mistaken with fully developed fluid flow which occurs when the normalized temperature profile also becomes constant. (Yunus A. Çengel, 2006). For laminar flow, the velocity profile in the fully developed region is parabolic, and for turbulent flow, the velocity profile curve is flattened, due to strong mixing in radial direction and eddy motion.

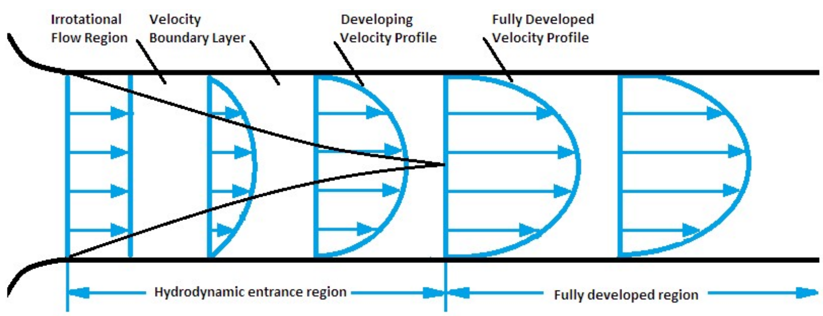

Figure 3. The developing velocity profile of a fluid entering a pipe (Hacisevki, 2017)

The flow condition, in which the unbounded fluid flows across the surface is called the external flow (Thue, 2014), with example being an air flow across the facade of the building. At low fluid velocities, the boundary layer thickness is large, and it is progressively decrease as fluid velocity increases. If there is a difference in temperature between the fluid and the surface, the heat transfer will occur in boundary layer. For external flow of air over a surface, the boundary layer can be assumed as a region between the surface, and region, where air velocity reaches 99% of free-stream velocity (Børve, 1987). At the surface, the velocity of air will be equal to zero due to the "no-slip" condition (Çengel, 2011). Since the viscous force slows down the boundary layer flow, as a result, certain amount of the mass has been displaced by the presence of the boundary layer (to satisfy the mass conservation requirement) thus decreasing the velocity of air near the boundary layer. Therefore, the velocity profile is neither linear nor parabolic, as in case of laminar internal flow. A laminar flat-plate boundary layer for external flow assumes a Blasius profile of velocity distribution, with higher velocities being located further away from the surface.

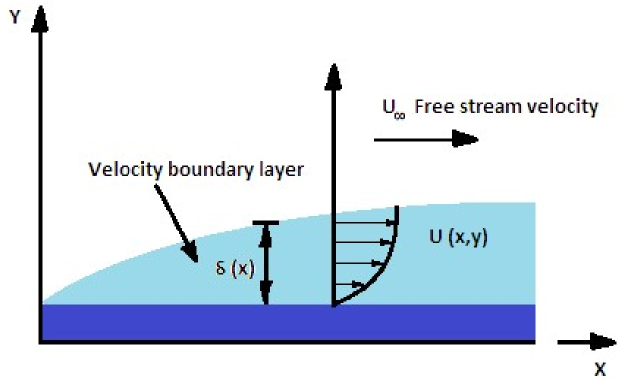

Figure 4. Flow over a flat plate (Puttkammer, 2017)

In flow analysis, streamlines, streaklines, pathlines and timelines are used to visualize fluid movement. A streamline is defined as a line, which is everywhere parallel to the local velocity vector $\vec{V}(x, y, z, t) = u\,\hat{i} + v\,\hat{j} + w\,\hat{k}$. Define

$$d\vec{s} = dx\,\hat{i} + dy\,\hat{j} + dz\,\hat{k}$$

as an infinitesimal arc-length vector along the streamline (Granger, 1995). Since this is parallel to $\vec{V}$, it follows that:

$$d\vec{s} \times \vec{V} = 0$$
$$(w\,dy - v\,dz)\hat{i} + (u\,dz - w\,dx)\hat{j} + (v\,dx - u\,dy)\hat{k} = 0$$

Separately setting each component to zero gives three differential equations, which define the streamline. The three velocity components *u, v, w,* must be given as functions of *x, y, z* before these equations can be integrated. To set the constants of integration, it is sufficient to specify some point x_0, y_0, z_0 through which the streamline passes. In 2D case $dz = 0$ and $w = 0$, and only the $\hat{k}$ component of the equation above is non-trivial. It can be written as an Ordinary Differential Equation (ODE) for the streamline shape *y(x)* as follows:

$$\frac{dy}{dx} = \frac{v}{u}$$

Equation 4. Differential equation for the streamline shape y(x) (Simon, 2017)

Again, *u(x, y)* and *v(x, y)* must be known to allow integration, and x_0, y_0 must be given to set the integration constants. A streakline is associated with a particular point *P* in space, which has the fluid moving past it. All points, which pass through this point, are said to form the streakline of point *P*. For example, a dye, steadily injected into the fluid at a fixed point *P* extends along a streakline. Unlike a pathline, which involves the motion of only one fluid element, *A,* in time, a streakline involves the motion of all the fluid elements along its length. Hence, the trajectory equations for a pathline are applied to all the fluid elements, defining the streakline. The pathline of a fluid element *A* is simply the path it takes through space as a function of time. An example of a pathline is the trajectory taken by one droplet of a dye, injected in the stream. This path is fully described by the three position functions $x_A(t), y_A(t), z_A(t)$, which can be computed by integrating the three velocity-field components *u(x, y, z, t), v(x, y, z, t), w(x, y, z, t)* along the path. The integration is started at time t_0, (e.g. the droplet injection time) from the element's initial position x_0, y_0, z_0 (e.g. the droplet injection point), and proceeds to some later time t as follows:

$$x_A(t) = x_0 + \int_{t_0}^{t} u\big(x_A(\tau), y_A(\tau), z_A(\tau), \tau\big)\, d\tau$$
$$y_A(t) = y_0 + \int_{t_0}^{t} u\big(x_A(\tau), y_A(\tau), z_A(\tau), \tau\big)\, d\tau$$
$$z_A(t) = z_0 + \int_{t_0}^{t} u\big(x_A(\tau), y_A(\tau), z_A(\tau), \tau\big)\, d\tau$$

The variable of integration τ runs from t_0 to t. In the case of steady flow, i.e. when the velocity vector-field does not change with time, the streamlines, pathlines, and streaklines coincide. For example, assume a particle A_1 on a given streamline reaches some point P_0, further on that streamline the equations governing the flow will force it to follow certain direction $\vec{x}$. As the equations that govern the flow remain the same when another particle A_2 reaches the point P_0, it will also follow the direction $\vec{x}$. If the flow is not steady and governing equations are not time-invariant, then when particle A_2 will reach the position P_0 the flow would have changed as the governing equations have changed and the particle A_2 will follow some new direction $\overrightarrow{x_n}$, reaching some point P_1 instead of P_0. Finally, a timeline is a set of fluid particles that form a line at a given instant. Example of a timeline is a velocity profile of the flow in the pipe, with, for instance timeline at t_1 being velocity profile at the pipe entrance and timeline at t_2 being fully developed flow in the same pipe.

Of prime importance in fluid mechanics is the Bernoulli equation, defined is eq. 5 as:

$$p_1 + \frac{1}{2}\rho v_1^2 + \rho g h_1 = p_2 + \frac{1}{2}\rho v_2^2 + \rho g h_2$$

Equation 5. Bernoulli equation (R.W.Johnson, 2017)

where, p_1, v_1 and h_1 are pressure, fluid velocity and altitude, respectively at some point P_1 and p_2, v_2 and h_2 are pressure, fluid velocity and altitude, respectively at some point P_2. From eq.5 it follows that if pressure, fluid velocity and altitude values are known for some reference point, these values can be obtained for any other point in the flow, as, in essence, Bernoulli equation postulates conservation of energy in the flow, and energy loses between the reference point and some point of interest are assumed to be insignificant (Børve, 1987).

Using the Bernoulli principle it is possible to derive some important concepts in the field of fluid mechanics. Consider, for example, a wing in flight. Assuming that $h_1 - h_2 = 0$ it follows that:

$$p_1 + \frac{1}{2}\rho v_1^2 = p_2 + \frac{1}{2}\rho v_2^2$$

Setting $v_2 = 0$ yields:

$$p_1 + \frac{1}{2}\rho v_1^2 = p_2$$

It is easy to see that, at the point of minimum flow velocities the pressure will be maximum. The case, where the flow velocity is equal to zero, thus yielding the point of maximum pressure in the flow, corresponds to the so-called "stagnation point". In the example of wing, at stagnation point the flow separation will occur, as streamlines will be forced to move around the wing in question. Expanding on this example, consider the case, where $p_2 = min\ \mathbf{p}$, i.e. some minimum pressure in the flow. It follows that at the point, corresponding to $p_2 = min\ \mathbf{p}$, the air velocity $v_2 = max\ \mathbf{v}$, i.e. the maximum velocity in the flow. For the wing, the point with minimum pressure and maximum velocity in the flow occurs at the suction side of the airfoil, located above the stagnation line. Since the pressure value is higher at the pressure side of airfoil (and by extension - air velocities at pressure side of airfoil are lower than those at the suction side), this difference in pressure, denoted ΔP, will result in the force, ΔF with the magnitude $\Delta F = \Delta PA$, where A is the wing area, to act normal to the suction side. This force ΔF can be recognized as the lift force and it is the primary mechanism behind the flight. The drag force using the Bernoulli principle can be explained due to pressure difference on the wing, redirecting the incoming airflow. In addition, the important component of drag force is the skin friction, arising due to viscous shear forces, exerted on the wing by the air in the boundary layer. Another example of Bernoulli principle application is the airflow over the terrain. Consider a rough terrain, consisting of either natural formations or artificial ones, such as buildings. Since the flow has to move around the obstacle, the flow will separate on the stagnation point. Past this point, the pressure in the flow will decrease and due to conservation principle, the flow velocity will increase, thus resulting in higher wind loads, acting on the suction side of the obstacle. The effect is amplified further if the obstacle has considerable height.

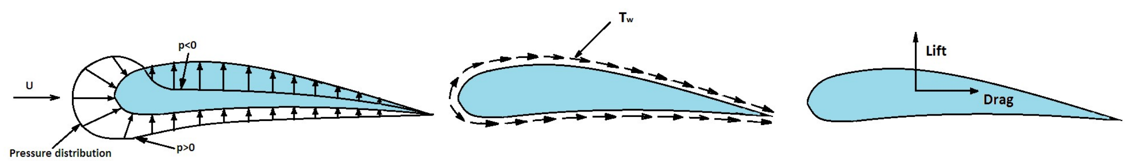

Figure 5. Force forces acting on an air force, respectively compressive forces, distribution of shear stress and resultant force (Munson, 2013)

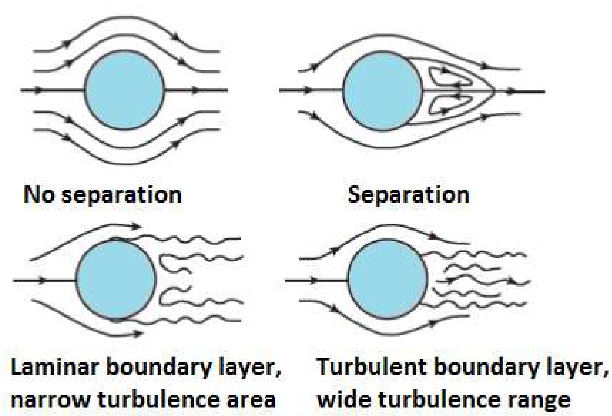

Figure 6.Flow around the cylinder (Munson, 2013)

In this case, pressure and height changes form eq. 5 will be the source of additional increase of the air velocity around the obstacle, in addition to increased wind speeds, occurring at higher altitudes, as the air velocity at ground level will be zero, due to no-slip condition and presence of planetary boundary layer, which will result in velocity profile to be not uniform (closely matching log wind profile for heights up to 100 meters). The log wind profile is given in eq. 7 as follows:

$$u_z = \frac{u_*}{\kappa}\left[\ln\left(\frac{z\text{-}d}{z_0}\right) + \psi(z, z_0, L)\right]$$

Equation 6. The log wind profile (Dorf, 2017)

where u_* is the friction (or shear) velocity (ms^{-1}), κ is the von Kármán constant (~0.41), d is the zero plane displacement, z_0 is the surface roughness (in meters), and ψ is a stability term where L is the Monin-Obukhovstability parameter. Under neutral stability condition, $\frac{z}{L} = 0$ and ψ drops out. However, surface roughness or stability information are typically not readily available. In this case log wind profile is approximated by wind profile power law as follows in eq.8 :

$$\frac{u}{u_r} = \left(\frac{z}{z_r}\right)^{\alpha}$$

Equation 7. Wind profile power law (Dorf, 2017)

where, u is the wind speed (ms^{-1}) at height z (m) and u_r is the known wind speed at a reference height z_r. The exponent α is an empirically derived coefficient that varies depending on stability of atmosphere. The wind profile power law in eq. 8 has an important application in wind engineering, known as wind gradient. The wind gradient is used to estimate the wind loads of an object and it is given in eq. 9:

$$u_z = u_g\left(\frac{z}{z_g}\right)^{\frac{1}{\alpha}},\ 0 < z < z_g$$

Equation 8. The wind gradient (Dorf, 2017)

in which u_z is the wind speed at height z, u_g is the gradient wind speed at gradient height z_g and α is the empirical exponential coefficient.

One of the most important concepts in fluid mechanics is the dimensionless parameter, known as Reynolds number, defined in eq. 10 as follows:

$$Re = \frac{\rho v L}{\mu}$$

Equation 9. Reynolds number (Brennen, 2017)

where ρ is the fluid density (kgm^{-3}), v is the fluid velocity with respect t the object (ms^{-1}), L is the characteristic length of the object (m) and μ is the absolute viscosity of the fluid ($kgm^{-1}s^{-1}$). The physical meaning of Reynolds number is that it describes the ratio of inertial forces to viscous forces in the fluid, due to different fluid velocities in relative internal movement in boundary layer. This relative movement generates fluid friction, which is a factor in developing turbulent flow. On the other hand, viscosity inhibits turbulence and more kinetic energy is absorbed by a more viscous fluid. The Reynolds number quantifies the relative importance of these two types of forces for given flow conditions, and allows to predict when turbulent flow will occur in some particular situation. Moreover, knowing the value of Reynolds number allows to predict presence of some phenomena in the flow. For example, if Reynolds number is in range of 10 < *Re* < 40 one can expect a laminar separation to occur with two steady vortices downstream of the object. If Reynolds number is increased further, let's say the Reynolds number lies in range 40 < *Re* < 1000 the steady vortices will be replaced by a periodic "von Kármán vortex street" (Marshall, 2001) due to unsteady separation of flow past the object. In the wind engineering the "von Kármán vortex street" is an undesirable effect, as this effect will lead to periodic crosswind forces to act on the objects behind the one, which sheds the vortices, thus leading to increased wind loads and undesirable vibrations in structures. The "von Kármán vortex street" effect is more pronounced for taller objects, as they can generate equally long "von Kármán vortex street".

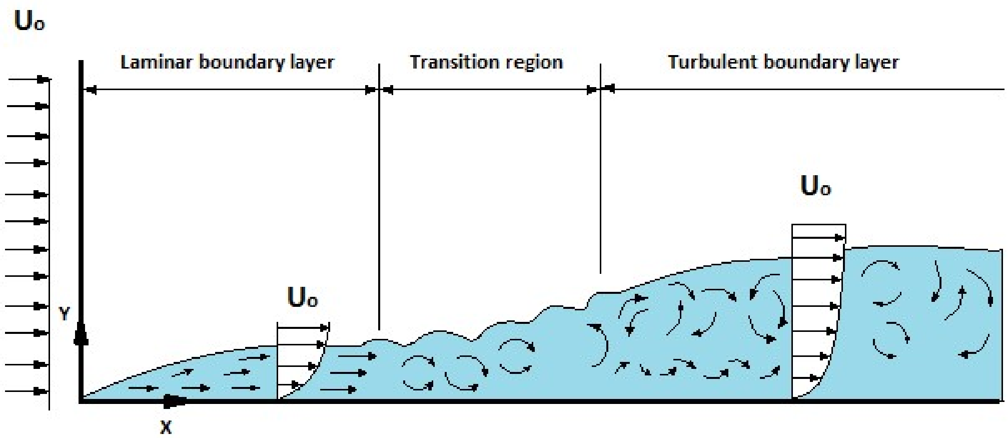

Figure 7. Development of boundary layers for flow across a surface (Çengel, 2011)

Finally, the motion of viscous fluids is governed by Navier-Stokes equations, which are the extension of Euler equations, which, in turn, describe the motion of inviscid fluids. Navier-Stokes equations can be obtained by applied Newton's second law to fluid motion, in addition to assumption that stresses in the fluid is the sum of pressure terms and diffusing viscous terms. The main difference between Euler and Navier-Stokes equations is that Navier-Stokes equations are not conservation equations, i.e. the net change in energy in not zero; but instead a dissipative system. i.e. thermodynamically open system operating not in thermal equilibrium. The Navier-Stokes equations are given in eq. 11:

$$\frac{\partial \rho}{\partial t}+\frac{\partial(\rho u)}{\partial x}+\frac{\partial(\rho v)}{\partial y}+\frac{\partial(\rho w)}{\partial z}=0$$

$$\frac{\partial(\rho u)}{\partial t}+\frac{\partial(\rho u^2)}{\partial x}+\frac{\partial(\rho uv)}{\partial y}+\frac{\partial(\rho uw)}{\partial z}=-\frac{\partial p}{\partial x}+\frac{1}{Re}\left[\frac{\partial \tau_{xx}}{\partial x}+\frac{\partial \tau_{xy}}{\partial y}+\frac{\partial \tau_{xz}}{\partial z}\right]$$

$$\frac{\partial(\rho v)}{\partial t}+\frac{\partial(\rho uv)}{\partial x}+\frac{\partial(\rho v^2)}{\partial y}+\frac{\partial(\rho vw)}{\partial z}=-\frac{\partial p}{\partial y}+\frac{1}{Re}\left[\frac{\partial \tau_{xy}}{\partial x}+\frac{\partial \tau_{yy}}{\partial y}+\frac{\partial \tau_{yz}}{\partial z}\right]$$

$$\frac{\partial(\rho w)}{\partial t}+\frac{\partial(\rho uw)}{\partial x}+\frac{\partial(\rho vw)}{\partial y}+\frac{\partial(\rho w^2)}{\partial z}=-\frac{\partial p}{\partial z}+\frac{1}{Re}\left[\frac{\partial \tau_{xz}}{\partial x}+\frac{\partial \tau_{yz}}{\partial y}+\frac{\partial \tau_{zz}}{\partial z}\right]$$

$$\frac{\partial(E_T)}{\partial t}+\frac{\partial(E_T)}{\partial x}+\frac{\partial(E_T)}{\partial y}+\frac{\partial(E_T)}{\partial z}=-\frac{\partial(up)}{\partial x}-\frac{\partial(vp)}{\partial y}-\frac{\partial(wp)}{\partial z}-\frac{1}{RePr}\left[\frac{\partial q_x}{\partial x}+\frac{\partial q_y}{\partial y}+\frac{\partial q_z}{\partial z}\right]$$
$$+\frac{1}{Re}\left[\frac{\partial}{\partial x}\left(u\tau_{xx}+v\tau_{xy}+w\tau_{xz}\right)+\frac{\partial}{\partial y}\left(u\tau_{xy}+v\tau_{yy}+w\tau_{yz}\right)+\frac{\partial}{\partial z}\left(u\tau_{xz}+v\tau_{yz}+w\tau_{zz}\right)\right]$$

Equation 10. The Navier-Stokes equations (Fefferman, 2017)

The Navier-Stokes equations, from top to bottom, consist of a time-dependent continuity equation for conservation of mass, three time-dependent conservation of momentum equations and a time-dependent conservation of energy equation. There are four independent variables in the problem, the *x*, *y*, and *z* spatial coordinates of some domain, and the time *t*. There are six dependent variables: the pressure *p*, density *ρ*, and temperature *T* (which is contained in the energy equation through the total energy E_T) and three components of the velocity vector: the *u* component is in the *x* direction, the *v* component is in the *y* direction, and the *w* component is in the *z* direction, All of the dependent variables are functions of all four independent variables. Other terms include, Reynolds number, *Re*, described previously, Prandtl number, *Pr,* which is the ratio of the viscous stresses to the thermal stresses, *q* terms are components of the heat flux, and τ terms are components of the stress tensor. Each component of the stress tensor is itself a second derivative of the velocity components.
The terms on the left hand side of the momentum equations are called the convection terms of the equations. Convection is a physical process that occurs in a flow of fluid in which some property is transported by the ordered motion of the flow. The terms on the right hand side of the momentum equations that are multiplied by the reciprocal of the Reynolds number are called the diffusion terms. Diffusion is a physical process that occurs in a flow of fluid in which some property is transported by the random motion of the molecules of the fluid. Diffusion is related to the stress tensor and to the viscosity of the fluid. Turbulence, and the generation of boundary layers, are the result of diffusion in the flow. The Euler equations, mentioned above, contain only the convection terms of the Navier-Stokes equations and, therefore, cannot model boundary layers. In addition, Navier-Stokes equations take into account the Froude limit, which is the ratio of the flow inertia to the external field, unlike the Euler equations. Note that all of the dependent variables appear in each equation. Thus, to solve a flow problem, it is necessary to solve all five equations simultaneously, therefore, the Navier-Stokes equations are a coupled system of partial differential equations (PDE) and could, in theory, be solved for a given flow problem by using simple calculus. But, in practice, these equations are too difficult and impractical to solve analytically, thus, further approximations and simplifications to the equations are set until the equations can be solved using a variety of techniques like finite difference, finite volume, finite element, and spectral methods. This area of study is called Computational Fluid Dynamics or CFD.

2. 5 Wind

2.5.1 Global atmospheric circulation

In order to understand the flow behavior of the air over terrain, it is necessary to understand the mechanisms, responsible for generation of winds. On a macroscale, the global atmospheric circulation is the primary mechanism responsible for formation of winds. There are four primary factors behind global atmospheric circulation:

1. Uneven solar heating of the Earth's atmosphere and surface.
2. Pressure gradient forces.
3. Coriolis force.
4. Friction (important near surface and in planetary boundary layer).

The difference in received solar radiation and flux density on Earth can be explained as follows. Assume an equal-area beams, having the same energy, of incoming solar radiation, striking the surface of the Earth. At the equator, this radiation will be focused on smaller area, thus heat flux density per area is maximum. On the other hand, at the poles, these "beams" will strike the surface at oblique angles, due to the shape of the Earth and axial tilt (effects of the Earth precession, unequal distribution of insolation, differential heating of land and water surfaces, and different albedos of surfaces are ignored, for simplicity), spreading the energy over larger area thus the heat flux density per area is minimum at the poles. For generality purposes, it can be said that the distribution of solar radiation per area follows the cosine law. The laws of thermodynamics require that any given system (Earth, in this case) should reach thermal equilibrium. Earth as a whole is in thermal equilibrium, but different latitudes are not. Thus an energy redistribution mechanism is required. Moving masses of air and ocean currents transport energy from locations with a surplus (equator) to those with a deficit (poles).

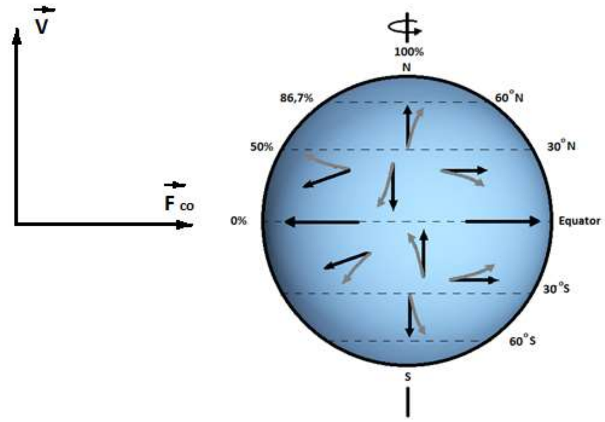

Figure 8. Coriolis force (Utaaker, 1991)

The heating of air masses causes them to expand in volume, thus decreasing the density of warm air. Due to this, heated air masses will rise, due to Archimedes principle (buoyant force and displacement of fluid), thus enabling two next factors in global atmospheric circulation - pressure gradient forces and Coriolis force. As heated air rises, it displaces the certain amount of mass, thus decreasing the pressure near the surface. When the heated air cools down in upper layers of troposphere, its density increases and eventually, this air will "sink" when its density surpasses a certain value, thus adding more mass over the area, where it sinks, increasing the surface pressure. Moreover, there is global difference in air density due to temperature, with air on equator being less dense than air at the poles. Combined, these factors lead to the appearance of horizontally distributed pressure gradient forces in global atmospheric circulation, as under basic laws of physics, the air will flow from regions with higher pressure to the regions with lower pressure, and these gradient forces are oriented normal to pressure isobars. Due to this movement, the Coriolis effects become significant for atmospheric circulation.

The Coriolis force is an inertial (fictitious) force, acting on the objects in relative motion to rotating relevance frame. The importance of Coriolis force (and by extent - any inertial force) from mathematical viewpoint, is that Newton's laws of motion should be preserved in a rotating reference frame (it is easy to verify, that in case of inertial reference frame Coriolis force does not exist), primarily concerning conservation of angular momentum. Angular momentum conservation means that if a rotating object moves closer to its axis of rotation, it must speed up to conserve angular momentum. Conversely, as a rotating object moves further from its axis of rotation, it must slow down. The Earth's curved surface means that objects are moving at very different speeds depending on their latitude, for example, at the equator (latitude 0°), an object is moving at a speed of about

1680 km/hr; the same object in St. Petersburg (60°N latitude), where the distance around a parallel of latitude is about half that at the equator, moves at about 840 km/h, while at the pole (latitude 90°), the object moves hardly at all due to the earth's rotation. Thus, if an initially motionless object moves from the equator northward, it will move closer to the Earth's axis of rotation, and will have to acquire speed in the direction of the earth's rotation. This results in an apparent deflection to the right. Similarly, an initially motionless object at the equator moving southward into the Southern Hemisphere will undergo an apparent deflection to the left. This apparent deflection is termed the Coriolis effect. The degree of deflection, or curvature, is a function of the speed of the object in motion and the latitudinal location of the object. The higher the latitude, the greater will be the Coriolis effect. In addition, the faster the object is moving, the greater will be the apparent deflection, and the greater the distance something must travel, the greater will be the Coriolis effect. Moreover, the inverse is true - the Coriolis effect decrease at lower latitudes, and it does not exist at the equator. Above Earth's surface, frictional drag is of little importance. At this point, the wind starts flowing down the pressure gradient and turns 90°, in response to the Coriolis effect. The pressure gradient is balanced by the Coriolis effect, and the wind, termed a geostrophic wind, flows parallel to the isobars. However, at or near Earth's surface (up to about 1000 m above the surface, corresponding to planetary boundary layer (Bjerg, 2012), frictional drag is important because it reduces the wind speed. A reduced wind speed in turn reduces the Coriolis effect, but the pressure gradient is not affected. With the pressure gradient and Coriolis effect no longer in balance, the wind does not flow between the isobars like its upper-level counterpart. Instead, a surface wind flows obliquely (about a 30° angle) across the isobars toward an area of low pressure (Dyrbye, 1989).
The idealized model of atmospheric circulation is a system of three cells in the latitude bands of 0° - 30° (Hadley Cell), 30° - 60° (Ferrel Cell) and 60° - 90° (Polar Cell) in each hemisphere and the jet streams. The three cells have the task of energy redistribution. This three-cell circulation pattern arises because of the unequal latitudinal distribution of radiation and the rotation of the Earth (Huang, 2014) (Qian Y, 2015):

1. A thermally direct circulation in the tropics (Hadley Cell), with rising motion around the equator and sinking motion at about 30° latitude.
2. A thermally indirect circulation in the middle latitudes (Ferrel Cell), with rising motion at 60° and sinking motion along with the Hadley Cell at about 30°.
3. A weaker direct circulation in the polar regions (Polar cell) with rising motion at about 60° and sinking motion over the pole.

A thermally direct circulation implies warm air rising and cold air sinking. Thermally indirect circulation implies the opposite, with warm air sinking and cold air rising. This is due to the fact, that thermally indirect circulation is driven by the cells on either side of Ferrel cell. Based on the idealized cell model, it is possible to establish an idealized model for global pressure belts as follows (Dyrbye, 1989) (Gabler, 2010):

- Centered approximately over the equator in the model is a belt of low pressure, or a trough. Since this is the region of greatest annual heating, it follows that the low pressure of this area, the equatorial low (equatorial trough), is determined primarily by thermal factors, which cause the air to rise.
- North and south of the equatorial low and centered on the so-called "horse latitudes", about 30°N and 30°S, are cells of relatively high pressure. These are the subtropical highs, which are the result of dynamic factors related to the sinking of convectional cells initiated at the equatorial low.

- Poleward of the subtropical highs in both the Northern and Southern Hemispheres are large belts of low pressure that extend through the upper-middle latitudes. Pressure decreases through these subpolar lows until about 65° latitude. Again, dynamic factors play a role in the existence of subpolar lows.
- In the polar regions have high pressure systems called the polar highs. The extremely cold temperatures and consequent sinking of the dense polar air in those regions create the higher pressures found there.

While this idealized model is reasonably good, it breaks down due to surface conditions (land vs. ocean). In reality the Earth is not covered by belts of high and low pressure but by a number of semi-permanent cells (cyclones and anticyclones). These cells undergo seasonal variations in position and intensity:

- In winter in Northern Hemispherethere are the Bermuda high, Pacific high anticyclones, characterized by easterlies to the south and westerlies to the north. The Siberian high and Canadian high are due to cold temperatures in the winter. The Southern Hemisphere in winter has better defined high pressure systems, located at midlatitude in Pacific, Atlantic and Indian oceans.
- The Icelandic low and Aleutian low cyclones in Northern hemisphere in winter are the locations of expected polar front. Continuous belt of low pressure that encircles the globe in the Southern Hemisphere in winter.
- In the summer Northern Hemisphere has low pressures over land. Subpolar lows practically disappear. Pacific High and Bermuda High define temperature regime in Northern Hemisphere.
- Intertropical convergence zone (ITCZ) pressure systems and wind belts shift north in July and south in January.

Finally, the characteristic wind belts from equator to pole are following (Kushnir & Stein, 2010):

- Trade wind belts: In the tropics, on both sides of the equator, lies a wide region where winds blow from east to west (easterlies) with a slight equatorward tilt. This region is named the trade wind belt, due to the steadiness of the air flow here.
- Intertropical Convergence Zone (ITCZ): The trade winds from the Northern and Southern Hemispheres converge into a narrow belt close to the equator, nowadays generally referred to as the Intertropical Convergence Zone (ITCZ). The convergence of the trade winds results in rising motion of the colliding ai rmasses. This region is also known as the doldrums, or the “equatorial belt of variable winds and calms”.
- Midlatitude westerlies: North and south of the trade wind belt (in the Northern and Southern Hemispheres, respectively) lie regions where winds tend to blow from west to east (westerlies), and are therefore referred to as the westerly wind belts. Here the winds are highly variable and unsteady, especially so during winter. In these regions, during wintertime, midlatitude storms and their frontal systems travel from west to east bringing frequent changes in weather.
- Subtropics: In between the trade wind regions lie the subtropics - regions of divergence and subsidence, the subtropical highs are areas, like the doldrums, in which there are no strong prevailing winds. However, unlike the doldrums, which are characterized by convergence, rising air, and heavy rainfall, the subtropical highs are areas of sinking and settling air from higher altitudes, which tend to build up the atmospheric pressure.

- Polar easterlies: Poleward from the westerly wind belt, winds with a generally easterly component prevail. The air here is cold, dry and stable, especially during winter, and is accompanied by subsidence from above.
- Polar front: The convergence zone between polar easterlies and midlatitude westerlies is referred to as the polar front. It separates between the cold (and dry) polar air, and the relatively warm (and more humid) midlatitude air. The polar front can be thought of as the average expression of the transient frontal systems that move along with midlatitude cyclones.

The surface wind distribution is not perfectly zonal. Winds are much weaker over land (friction over land is larger than over the oceans, and high variability is the reasons for a low average). Along the coasts, winds deviate quite a bit from zonal symmetry.

2.5.2 Local wind systems

Local topography heavily influences air temperature and wind formation conditions. Difference in heating and cooling of different terrain types is the cause of local wind circulation systems. There are a few different types of local wind system, which are often a response to local landform configurations. These configurations typically include the presence of large bodies of water, for example, oceans, large lakes, or large, rough terrain effects, such as mountains, high hills and ridges.

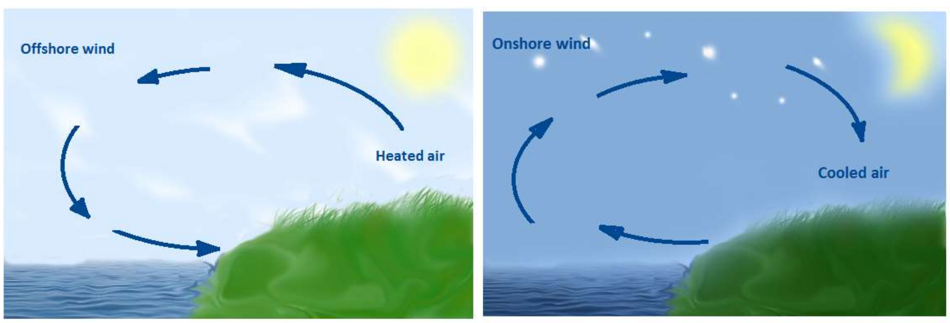

Figure 9. Local wind system at the coast (Utaaker, 1991)

Near the coast the air above water and land will be heated differently due to differential heating of land and water, caused by difference in heat capacity of land and water (Utaaker, 1991), thus creating diurnal (daily) land breeze - sea breeze cycle. During the day, when the land and, consequently, the air above it, is heated more quickly and to a higher temperature than the nearby body of water, the air above the land expands and rises. At night, the land and the air above it cool down more quickly and to a lower temperature than the nearby water body and the air above it. Consequently, there is a higher pressure build-up over the land and air flows out toward the lower pressure over the water, creating a land breeze.

Figure 10. Local wind system in mountain ranges (Utaaker, 1991)

The terrain effects are the source of katabatic winds (Utaaker, 1991), also known as drainage winds, and mountain breeze - valley breeze cycle, analogous to land breeze-sea breeze cycle. Katabatic winds are local to mountainous regions and can occur only under calm, clear conditions. Cold, dense air will accumulate in a high valley, plateau, or snowfield within a mountainous area. Because the cold air is quite dense, it tends to flow downward, escaping through passes and pouring out onto the land below. Drainage winds can be extremely cold and strong, especially when they result from cold air accumulating over ice sheets (Gabler, 2010). If the terrain is extremely steep and rough, the cold air flow will occur in "shock" behavior downward the mountain side and it can reach very high velocities (Utaaker, 1991). Somewhat similar in mechanism to the land breeze–sea breeze cycle, discussed previously, there exists a daily mountain breeze - valley breeze cycle. However, the difference of this particular cycle, compared to sea breeze - land breeze cycle, is that the differential heating is caused not by difference in heat capacity, but rather by in difference to solar heating exposure. During the day, when the valleys and slopes of mountains are heated by the sun, the high exposed slopes are heated faster than the lower shadier valley. The air on the slope expands and rises, drawing air away from the valley and up the sides of the mountains. This warm daytime breeze is the valley breeze, named for its place of origin. Clouds, which can often be seen obscuring mountain peaks, are actually the visible evidence of condensation in the warm air rising from the valleys. At night, the valley and slopes are cooled because Earth is giving off more radiation than it is receiving, thus the air cools and sinks once again into the valley as a cool mountain breeze (Utaaker, 1991). Finally, another type of local wind system, influenced by both terrain effects and proximity to water bodies (although, not as close as in case of sea breeze - land breeze cycle) is the foehn-type winds. Foehn-type winds occur when air originating elsewhere must pass over a mountain range. As these winds flow down the leeward slope after crossing the mountains, the air is compressed and heated at a greater rate than it was cooled when it ascended the windward slope. Thus, the air enters the valley below as warm, dry winds. The rapid temperature rise brought about by such winds has been known to damage crops, increase forest-fire hazard, and set off avalanches (Gabler, 2010).

2.5.3 Wind effects around buildings, structures

Wind impact is considered to be one of the most important parameters when it comes to building physics and design. This is due to the fact that wind affects many different parameters such as (Thue, 2014):
- Air quality
- Static and dynamic stresses
- Natural ventilation
- Wind effects

- Sheltering and comfort
- Snow storage
- Heat losses

When air flow encounters physical obstacles it will decelerate while causing excessive pressure, due to Bernoulli principle, on windward side and a pressure drop on leeward side. Around suction zones, velocity increases, while vortices occur in the pressure zones (Bjerg, 2012). Increase in wind speed will cause the pressure differential to increase, which in turn will make turbulence effects more pronounced. Air flow patterns and amount of turbulence will vary, depending on building placement and its geometric design. Generally speaking, buildings and objects with streamlined design will tend to minimize turbulence, caused by air flow. A rounded building design makes it possible to reduce the turbulence that occurs at the corners, but such a design has a higher possibility to induce vortex shedding, especially taller ones, when compared to an edged building.

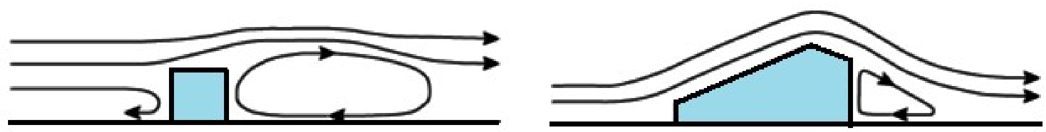

Figure 11. Flow patterns in different forms of construction (Børve, 1987)

The location of buildings with respect to prevailing wind direction determines the behavior of flow patterns. The location forms the basis for estimating the location of pressure and suction zones around the buildings the expected extent of these zones and their effects. A building whose the longer side is positioned against the wind direction will decelerate the airflow and create a large turbulence field on the leeward side of it. If the short side of the building is positioned against the wind direction, the airflow will move along the building, and as a result considerably smaller turbulence affected area will form. A diagonal position will create an asymmetric flow field with more complex turbulence pattern (Bjerg, 2012).

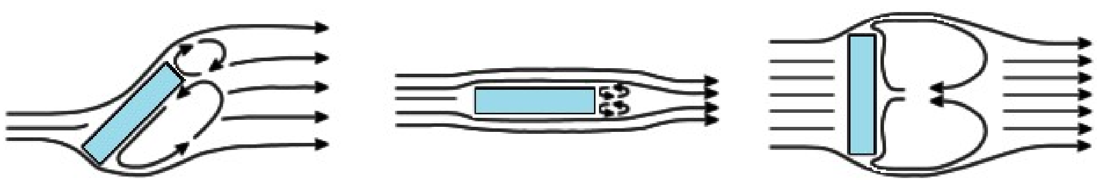

Figure 12.Flow pattern for different rotation of building (Børve, 1987)

Single buildings that extend over surrounding buildings can cause strong local air flows. Wind that moves above the overall height of a building area will, due to the effect on wind gradient, will have a significantly increased velocity, compared to the ground level. When this high speed wind interacts with a tall building a high pressure pocket will form at windward side of the building which will lead to strong downstream flow, known as downwash, causing turbulence at ground level (Givoni, 1998). The issue increase further with increase in building height and air velocities. It is possible to make some design alterations to counter this to an extent. For example, larger lower part of the building can deflect and dampen some part of this downstream flow, reducing the turbulence at ground level, thus creating more comfortable outdoor area.

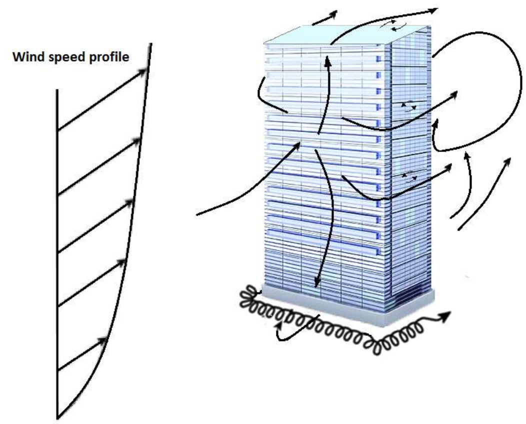

Figure 13. Wind flow around the tall building (Hanssen-Bauer, 2017)

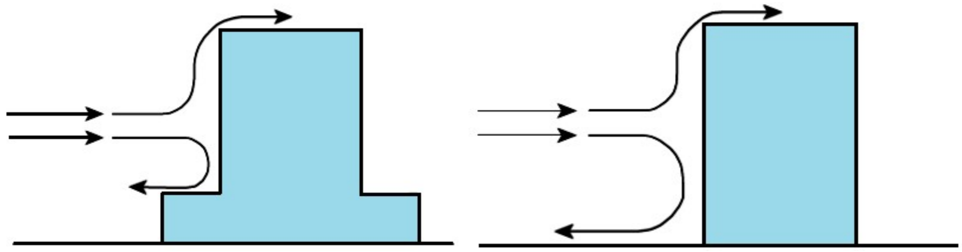

Figure 14.. Effect on extended lower part on downstream wind flow from a tall building (Asplan, 2017)

The landscape has a significant importance for the location of buildings. Different types of builiding arrangements were created to adapt to different natural conditions. For example, in Norway, these configurations vary from county to county. In valleys, buildings were placed in the form of rows on the sunny side of valley, while the valley floor was used for agricultural purposes. This configuration takes advantage of the solar conditions and adapts the building locations to the terrain. In another example, locations with flatter landscapes utilized square configurations. Such configuration consists of several buildings that together create an inner open space, sheltered from the wind effects, thus making this area comfortable for outdoors activity Another typical configuration is cluster. Such configuration has a more random spread of the buildings and complex airflow patterns and was common in hilly terrain, especially in western Norway (Thiis-Evensen, 2007).

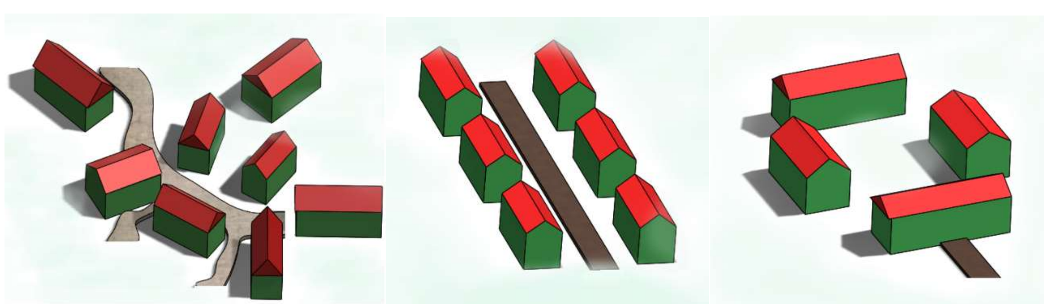

Figure 15. Cluster, row and square configuration (Thiis-Evensen, 2007)

When buildings are grouped, the principles of wind circulation around single buildings will be applicable, but at the same time, a more complex pattern of local wind flows and effects will be present. The complexity will increase with the number of buildings and their design, height, distance, building patterns etc (Bjerg, 2012). While the historic configuration patterns, described previously has evolved significantly over time, there are still many similarities present in today's urbanization patterns. The principle of placing buildings in clusters is widely used to prevent the wind from being funneled between the houses, as it is desirable for the wind to flow around and above the group of houses, thus it is advantageous to use building patterns where the buildings are placed around an open area, reminiscent of a typical square configuration. The principle here, is that buildings in this arrangement will provide sheltering for an open internal area.

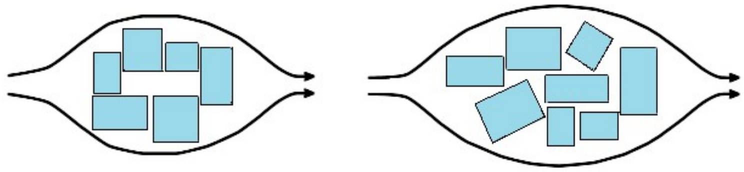

Figure 16. Urban construction patterns (Asplan, 2017)

Residential areas, adapted to the terrain are a useful method for shielding residential areas from the wind. This can be done, for example, by placing buildings, according to the terrain, so that the wind flows in a similar patterns. A combination of lower and taller buildings can be used to produce a sort of overhead sheltering configuration, that forces the wind to flow over the buildings. Placement of buildings in a lowland is another method to achieve the wind flow over the residential area. One possible issue with arranging the buildings in such a configuration, is that instead of passing over the arrangement, wind can flow downstream from top of the buildings, due to downwash effect, and into the streets, with large distances and height differences between buildings magnifying the effect. This will create turbulence at outdoor areas at ground level, that can be perceived as uncomfortable.

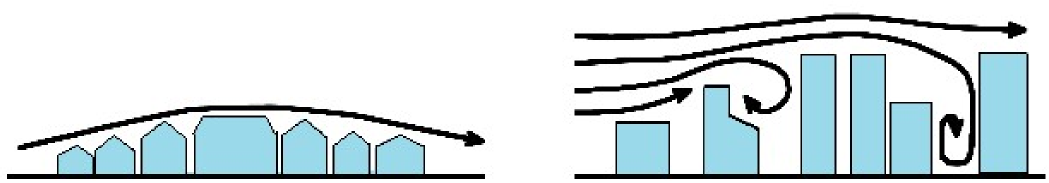

Figure 17. Overhead sheltering structure and downwash effect from tall buildings (Asplan, 2017)

The placement of buildings has a major impact on local wind conditions. Open city spaces and building locations can, when subjected to wind, create effects that result into significant levels of turbulence and increased wind speeds. In straight streets, aligned parallel to the wind direction, the wind will flow down the street and due to interaction with buildings, increase in velocity is expected at the center of the street, reminiscent of velocity profile in internal flow. The street span will act as a leading corridor, where the wind is constrained by the buildings and a "wind tunnel" will form. This type of wind movement is called the corridor effect. Narrower streets will constrain the air flow further. A street span, that narrows before it widens again will function as a funnel, hence the name of the funnel effect. The inflow and outflow of the funnel may have significant pressure differences, and due to Bernoulli effect, that will cause corresponding increase in velocities. The strongest wind will occur at the narrowest section, where the pressure is lowest (Meteorological institute , 2009).

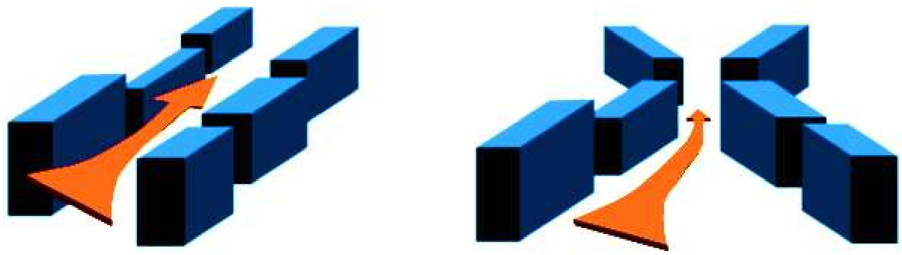

Figure 18. Corridor effect and funnel effect (Houlberg, Wind and shelter in settlements, 1979)

2.5.4 Wind effects on the roof of buildings

Wind can create significant pressure stress on structures and buildings. When air flows towards a building, the flow will be deflected around and above the building. The building's external walls and roof surfaces will have areas with overpressure and underpressure. Pressure conditions on ceilings will depend on roof shape and inclination angle (Thue, 2014) . Buildings with steep roofs, exceeding 30° inclinations will have pressure zones on windward side and suction zones on the leeward side. Roofs with angles less than 20° and flat roofs will have suction forces that act on the entire roof (Dyrbye, 1989). Unlike flat roofs, roofs with steep slopes can develop a high amount of overpressure (Thue, 2014).

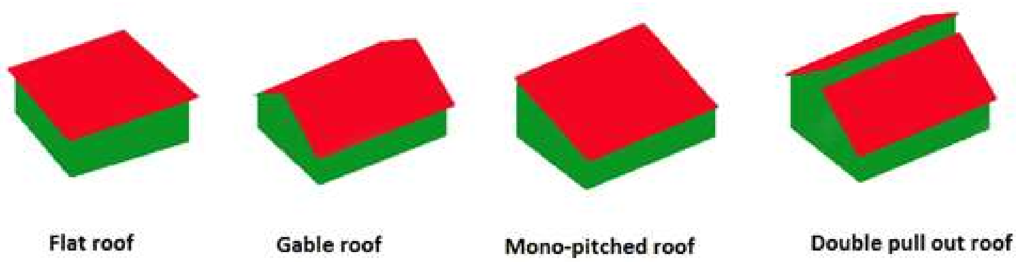

Figure 19. Types of roof (Ramstad, 2014)

Along the surface there will often be big differences in speed and pressure. The biggest pressure drops occur at corners and edges. Since wind speeds can change in a short period of time, the pressure and suction forces may also change. Gabled roofs with a slope angle between 20° and 30° may have both suction and pressure forces acting on the roof surface at the leeward side (Dyrbye, 1989). If porches, terraces, balconies, etc. are used in construction on the windward side of a building, pressure distribution will occur in the upward direction of the structure. If there is a large overpressure on the underside and underpressure on the upper side, these superstructures will be particularly exposed to wind induced damage (SINTEF Byggforsk, 2003). The use of such superstructures must be carefully considered in relation to location and design.

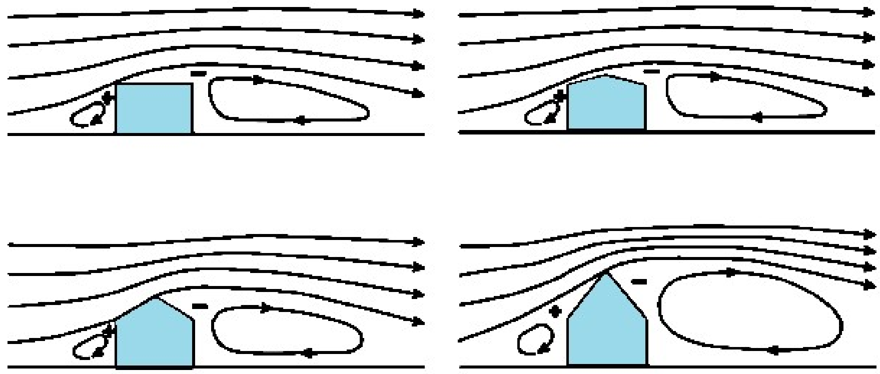

Figure 20. Pressure distribution for different roof shapes (Dyrbye, 1989)

In order for structures to withstand large wind loads, they must be dimensioned properly. For wind load calculations, it is necessary to have information about in which municipality building will be built, local topography data, local climatic data, roof design data, and the location of the building in relation to surrounding buildings (SINTEF Building Research, 2003). Each municipality has recorded average wind speeds over a 50-year return period. Wind loads, generated on a surface of the building, will vary on different parts of a surface and on different sides of the building. Since the wind loads has large variations, for simplicity, the form factors are used for different types of buildings. These form factors are based on measurements made in wind tunnel model experiments (Dyrbye, 1989). By following established standards and adapting values to the particular development project, wind loads can be calculated.

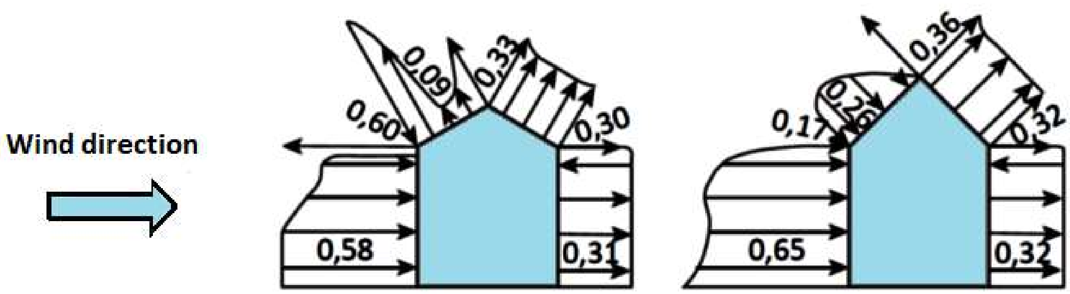

Figure 21. Pressure distributions for different form factors of buildings (Dyrbye, 1989)

2.5.5 Wind effects in terrain and landscape

Wind flow in relation to terrain formations, vegetation and buildings is a determining factor for local wind conditions. By studying a physical environment, one can gather information and techniques to adapt the building pattern to each specific project area. Wind that does not encounter obstacles and is undisturbed, will behave as a laminar flow (Bjerg, 2012). Turbulence occurs when the wind encounters obstacles, resulting in creation of vortices. Terrain formations will affect wind movement and velocity. Flat open areas will not have major obstacles, and the wind will only be affected by surface roughness and vegetation. In a rough landscape, terrain formations could change the direction and the velocity of wind. At hilltops, the air masses will be compressed, causing the increase in velocity (Bjerg, 2012). Subsequent depressions in the terrain will cause air masses to expand and cause a reduction in wind speed. On steep slopes the wind is deflected upwards. At the edges of the slope and at the bottom of the hill there may be turbulence, due to suction forces.

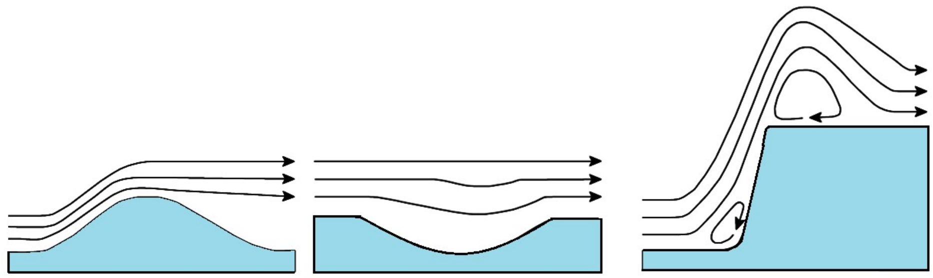

Figure 22. Flow patterns for different terrain formations (Houlberg, Wind and shelter in settlements, 1979)

2.6 Local wind conditions (Larvik)

The development area at Martineåsen in Larvik is on a hill, and has a reputation for being very windy. This area has a terrain with large height differences, which are covered by forest. Some of the locations are relatively bare, without any other nearby buildings. The vegetation consists of bushes and clusters with trees. Eastern and central zones of Martineåsen area have little shielding from the wind and the area can experience hard winds. The new building structure should be planned based on prevailing wind directions, so that the wind can be managed as best as possible, mostly when it comes to the design of outdoor areas.

A prevailing wind direction provides information that is important in planning development areas. The prevailing wind direction is the wind direction, which is most probable wind direction in the given area. This information is measured at measurement stations, and the results can be obtained in the form of windrows. Information on prevailing wind direction allows to estimate expected wind movement and locations of sheltered areas around a building. With good planning it is possible to place outdoor living areas such that they are sheltered from the wind in addition taking advantage of the wind, by placing areas along the wind direction to avoid precipitation accumulation. In order to prepare an analysis of local wind conditions for the planned area, the local prevailing wind directions are analyzed first. However, there are no available wind or weather observations for the development area at Martineåsen.

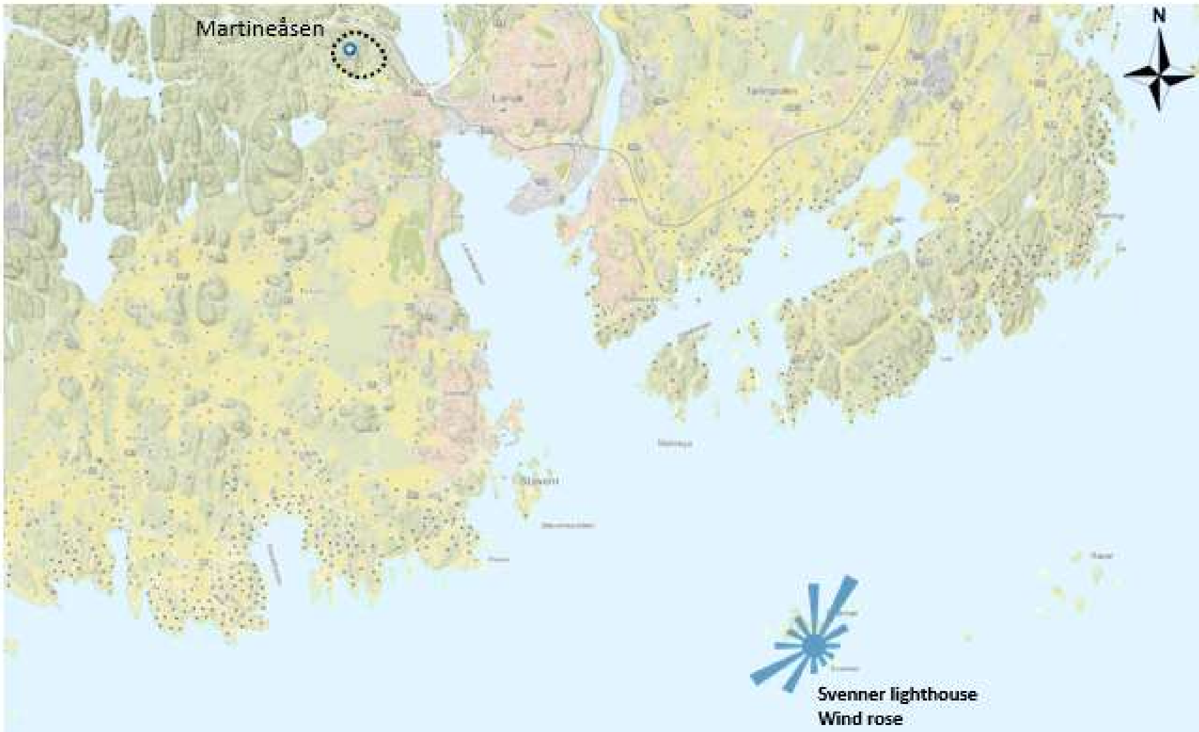

Figure 23. Map of Larvik. Annual wind rose located at the measurement station (Meteorological institute, 2017)

The closest measurement station is the Svenner lighthouse, registered as metrological station 29950, which is located at the distance 13.8 km from Martineåsen and it is located 15 m above sea level.

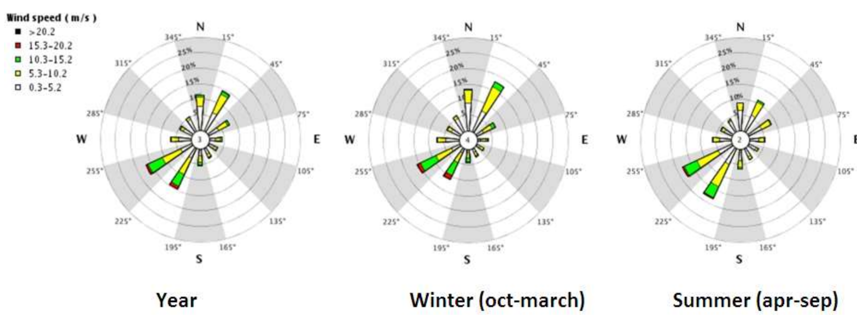

Figure 24. Wind rose Svenner lighthouse for period 2000-2015 (DNMI, 2017)

From the wind rose, pictured in the fig. 25, which is taken from Norwegian Institute of Meteorology and is based on the measurements from Svenner lighthouse, one can see that the prevailing wind direction in winter period (from October to March) is the west-southwest (WSW) – southwest (SW) direction, with maximum wind speeds being around 15–20 m/s and mean wind speeds of approximately 10 m/s. In addition, there is another direction with high probability of wind, as can be seen from fig. 25, in the northeast (NE) direction, however, the maximum and mean values, are lower than that of WSW-SW direction, with maximum wind speed being in the range of 10–15 m/s and the mean wind speed being roughly 5 m/s.

In the summer period, (from April to September) the prevailing wind directions is southwestern (SW) one. Compared to the winter period, the NE wind direction is considerably less likely to occur, while

the windrow, spanning from 195° to 225°, has a significant increase of frequency, thus giving overall wind direction as SW. In addition, compared to winter period, the maximum wind speed range is the same in summer, being 15-20 m/s, however, there is higher frequency of occurrence of moderate winds (5-10 m/s) when compared to moderately-strong (10-15 m/s) and strong (15-20 m/s) winds in winter period, thus giving smaller mean wind speed in summer period, being roughly 7 m/s.
Overall, from annual windrose, given in fig. 25 it can be seen that the “annual” prevailing wind direction is the one from 225°-255° windrow, which translates to WSW-SW direction. While the 195° – 225° windrow, corresponding to the southwest (SW) – south-southwest (SSW) direction, is not as “developed” as the 225° – 255° one, it is still quite significant, nonetheless. Thus, it might be advantageous to consider SW direction as the prevailing wind direction throughout the year.

2.7 Martineåsen topography

Larvik is town and municipality in Vestfold county, located in the southern Norway. The municipality covers an area of 530 km^2 and has a population of 41,211. Larvik is an important transportation hub to southern and eastern Norway and has a daily ferry connection to Denmark. The municipality of Larvik has developed a regulation plan for Martineåsen with the aim to build between 1500 and 3000 new buildings in the next 20 years (Larvik municipality, 2007). The plan for Martineåsen region includes the buildings, school, walkways, ski resort, and various nature and outdoor areas.

Figure 25.Location of the plan area (dashed field), indicating prevailing wind directions (Google map, 2017)

With the support of Outdoor Environment Technology AS, Rambøll Norge and the Larvik municipality will develop a new residential area in Martineåsen, to the northwest of the center of Larvik. The Martineåsen is situated at a ridge, just south of the E18 road and the lake Farris, in the direction of Porsgrunn. From Martineåsen there is a view of lake Farris, in the northeastern direction, Larvik fjord in the southern direction and the surrounded by forest and farmlands, at the foot of the hill. The development area is located on a plateau, between 95-160 meters above sea level, which is known to be a particularly windy area. The project area is located on a relatively rough terrain and it is especially rough and hilly in the northern and central directions. Most of Martineåsen area is covered by forest. The landscape is relatively unused and is linked to the city by the route E18 which goes further south. The natural landscape is overlooking the fjord and is located at the short distance from the urban environment, providing an attractive development area with unique qualities.

2.8 Wind effects on outdoor and activity

Throughout the years, man has adapted to different climatic conditions. This applies to both settlement structures and clothing. In order to be able to live in varying climatic conditions, the heat balance can be adjusted by means of clothing and activity level. By increasing the amount of clothing, heat insulation can be increased and heat loss reduced. Similarly, at increased activity levels the person needs less clothing. In outdoors conditions, high wind forces will change the temperature perception, as it can be "felt" that the air temperature differs from what measurements indicate. To describe how a given air temperature along with wind conditions will be experienced by a person, the concept of apparent temperature is introduced. A thermometer only measures the air temperature irrespective of wind conditions. The apparent temperature can therefore be higher or lower than the actual temperature, measured from a thermometer. To showcase how heat loss from human skin is affected by the wind force, a separate table has been developed, called the wind-chill index. Wind-chill index is the perceived decrease in air temperature, felt by the body on exposed skin, due to the flow of air. The table is based on results from experiments by Paul A. Siple and Charles F. Passel in the Antarctic, but in 2001 an updated formula was introduced (Meteorological Institute, 2016). The eq. (11) indicates wind-chill index, *W*, where *T* is the temperature in (^{o}C) at 2 m height, *V* is wind speed (kph) at 10 meters altitude (magl):

$$W = 13.12 + 0.6215T - 11.37V^{0.16} + 0.3965TV^{0.16}$$

Equation 11. Wind chill index (Naylor, 2017)

Wind	**Wind speed, m/s**	**Air temperature, [°C]**												**Apparent temperature [°C]**
		5	0	-5	-10	-15	-20	-25	-30	-35	-40	-45	-50	
Mild wind	1,5	4	-2	-7	-13	-19	-24	-30	-36	-41	-47	-53	-58	
	3	3	-3	-9	-15	-21	-27	-33	-39	-45	-51	-57	-63	
Light breeze	4,5	2	-4	-11	-17	-23	-29	-35	-41	-48	-54	-60	-66	
	6	1	-5	-12	-18	-24	-31	-37	-43	-49	-56	-62	-68	
Soft breeze	7,5	1	-6	-12	-19	-25	-32	-38	-45	-51	-57	-64	-70	
	9	0	-7	-13	-20	-26	-33	-39	-46	-52	-59	-65	-72	
Light breeze	10,5	0	-7	-14	-20	-27	-33	-40	-47	-53	-60	-66	-73	
	12	-1	-7	-14	-21	-27	-34	-41	-48	-54	-61	-68	-74	
Little breeze	13,5	-1	-8	-15	-21	-28	-35	-42	-48	-55	-62	-69	-75	
	15	-1	-8	-15	-22	-29	-35	-42	-49	-56	-63	-70	-76	
Stiff breeze	16,5	-2	-9	-15	-22	-29	-36	-43	-50	-57	-63	-70	-77	
	18	-2	-9	-16	-23	-30	-37	-43	-50	-57	-64	-71	-78	

Strong gale	19,5	-2	-9	-16	-23	-30	-37	-44	-51	-58	-65	-72	-79	
	21	-2	-9	-16	-23	-30	-37	-44	-51	-59	-66	-73	-80	
Small storm	22,5	-3	-10	-17	-24	-31	-38	-45	-52	-59	-66	-73	-80	
	24	-3	-10	-17	-24	-31	-38	-45	52	-60	-67	-74	-81	
Freezing hazard		Small				Increased	Big			Very big				
							< 10 min			< 2 min				

Table 5. Wind chill index (Meteorological institute, 2017)

Wind chill numbers are always lower than the air temperature for values where the formula is valid. When the apparent temperature is higher than the air temperature, the heat index is used instead. For outdoor activity, the level of comfort is experienced differently depending on the type of outdoor activity. A separate set of criteria has been developed to define a person's tolerance for wind exposure, called Lawson's comfort criteria. Lawson's comfort criteria provide a classification of wind comfort based on type of outdoor recreation and activity. The comfort criteria provide an overview of what is considered acceptable and unacceptable wind speed and percentage of time spent in the area. The division allows to assess whether an area will be comfortable, based on wind speed and the planned use of the area in question.

Recreation/Activity	Acceptable	Unacceptable
Pedestrian sitting	4% > 3.5 m/s	1% > 5.5 m/s
Building entrances	4% > 3.5 m/s	6% > 5.5 m/s
Pedestrian standing	6% > 3.5 m/s	6% > 5.5 m/s
Pedestrian walking	6% > 5.5 m/s	4% > 8.0 m/s
Business walking	2% > 8.0 m/s	2% > 10.5 m/s
Roads and parking places	2% > 10.5 m/s	6% > 10.5 m/s

Table 6. Lawson's comfort criteria (Vindteknikk, 2017)

A disadvantage of Lawson's comfort criteria is that temperature is not taken into account. The comfort criteria were developed in England and therefore are based on local conditions. The issue with this, is that different locations will be subjected to different temperatures, and, therefore, it is not beneficial to use these criteria as a standard. In regions with cold climate, wind speeds that are comfortable in warmer climates, will, in turn, be quite uncomfortable. Lawson stated that it was impossible to incorporate temperature into the comfort criteria, as it was impossible to link temperature and wind velocity together, and that only way could be by designing different set of criteria for different locations and seasons (Eaton, 1977).

4. Method and model

3.1 3D model

Based on development plans from Larvik municipality the following building types has been modeled in 3D and used in simulations:

1. A block type two-storey buildings. This type of buildings in only present in eastern and southern parts of area A.
2. A two-storey single houses with garage.
3. A one-storey single house. Same as above, but without terraces. This type of buildings, is by far the most common one in simulation, and they are reminiscent of typical Scandinavian and other European single houses.

All the buildings is simulations have heights, varying between 4.5 and 6 meters. The block-type buildings have flat roofs, while single houses has inclined roofs. The visual representation of all three types of buildings are given in fig. 27.

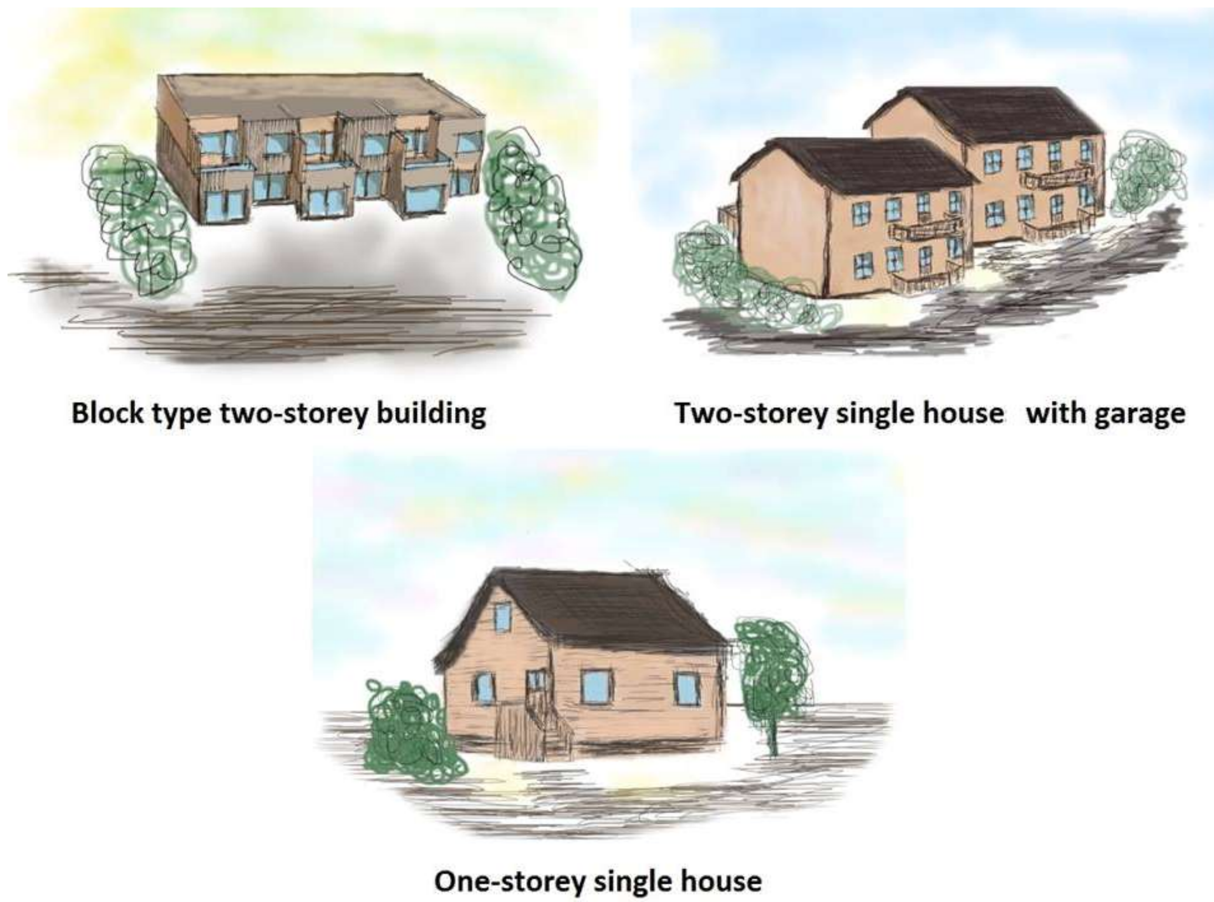

Figure 26. Types of buildings

3.2 Development of design proposals

Based on Larvik's municipality project plan for the development area, the entire project area can be divided into two distinct subareas:

1. Area A, located mostly in lowland, situated at the eastern side of the project area.

2. Area B, located in the elevated terrain (when compared with area A), situated in the central and northern regions of the project area.

In addition, in simulations the so-called "area C" is present. Area C consists of areas A and B combined, or, in another words - it is representative of entire project area. The reason for division of areas into such an arrangement is to study air flow behavior in one of each terrain types (rough high ground for area B and more-or-less flat less elevation in area A) and later check, with the help of simulations of area C is there are any abnormalities present, when comparing results from each individual areas A, B and C. The buildings in the area A, according to Larvik municipality representatives, are a few storey high, block-type buildings. The buildings in area B are mostly one-two storey single houses, typical for Scandinavia and other European countries. At least some of them are having porches and terraces in the design, which has been accounted for in simulations. All buildings in all areas are located along prevailing wind direction in addition being aligned along the roads and provide maximum exposure to the sunlight.

For all the areas, A, B and C, following simulations were performed, in order:

- Terrain and local vegetation present. Wind direction is south-southwest (SSW), which corresponds to the prevailing wind condition for Larvik, as it can be seen from windrose in fig. 25.
- Terrain, local vegetation and buildings are present.
- Terrain, vegetation and buildings are removed. Preprocessing is restarted with "elevated terrain" setting at 1.75 meters from the ground level (magl) elevation.
- For analysis: terrain, vegetation and elevated terrain are present. Buildings are not present.

The reasons for this set of simulations and in this particular order are as follows. First, it is necessary to understand the air flow behavior, any, if all, distinct patterns and specifics in "undisturbed" terrain, corresponding to the current conditions on the project area, i.e. rough terrain with significant number of local vegetation present. Second, some of the local vegetation is removed, according to area development plans and buildings are added instead. This simulation, in essence, will provide the information about air flow behavior and wind conditions on the site, when the project is finished and to serve as input data for the next simulation in series.

For the next simulation, the terrain, vegetation and buildings are removed. However, the data is not deleted. Instead, the output results from previous simulation are being used as an input here. Afterwards, the simulation is restarted with "elevated terrain" option enabled and set to 1.75 magl. The main goal here is to achieve the results for air flow, when it is unaffected by boundary layer effects and roughness of the terrain, vegetation and buildings, which will most likely cause excessive turbulence in layer, close to the ground. Following that, the results from two preceding simulations, i.e. one with elevated terrain and one with terrain, vegetation and buildings are merged in order to study air flow behavior in full, at all layers.

Based on the simulation results, some building locations in areas A, B and C has been altered, due to exceedingly high wind speeds and resultant wind stress acting on some of the buildings. Following this adjustment, an additional set of simulations has been conducted for areas A, B and C. The simulations have the exact same input parameters and properties as those, described above, so for brevity purposes they will not be repeated here. The only difference being another wind direction - north-northeast (NNE) being tested for new configuration, in addition to SSW wind direction. The comparison between two configurations are given in figs. 28 and 29, as follows:

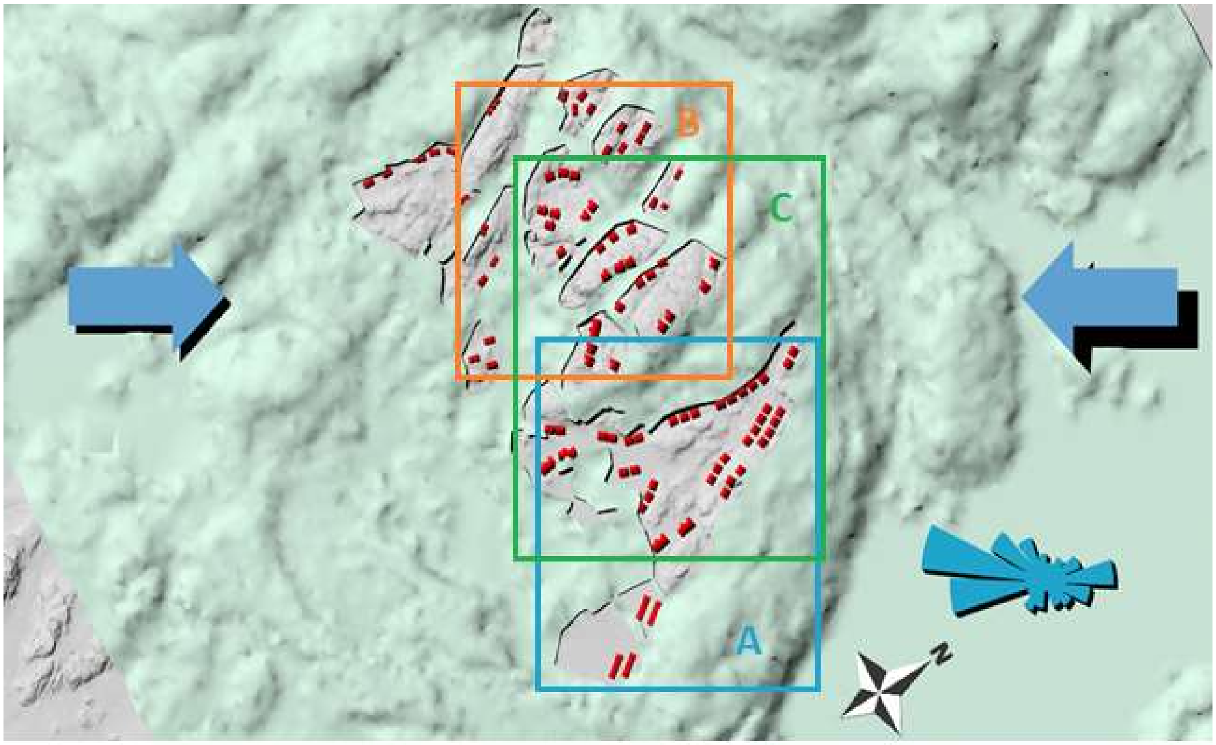

Figure 27. Original configuration of buildings, wind direction SSW

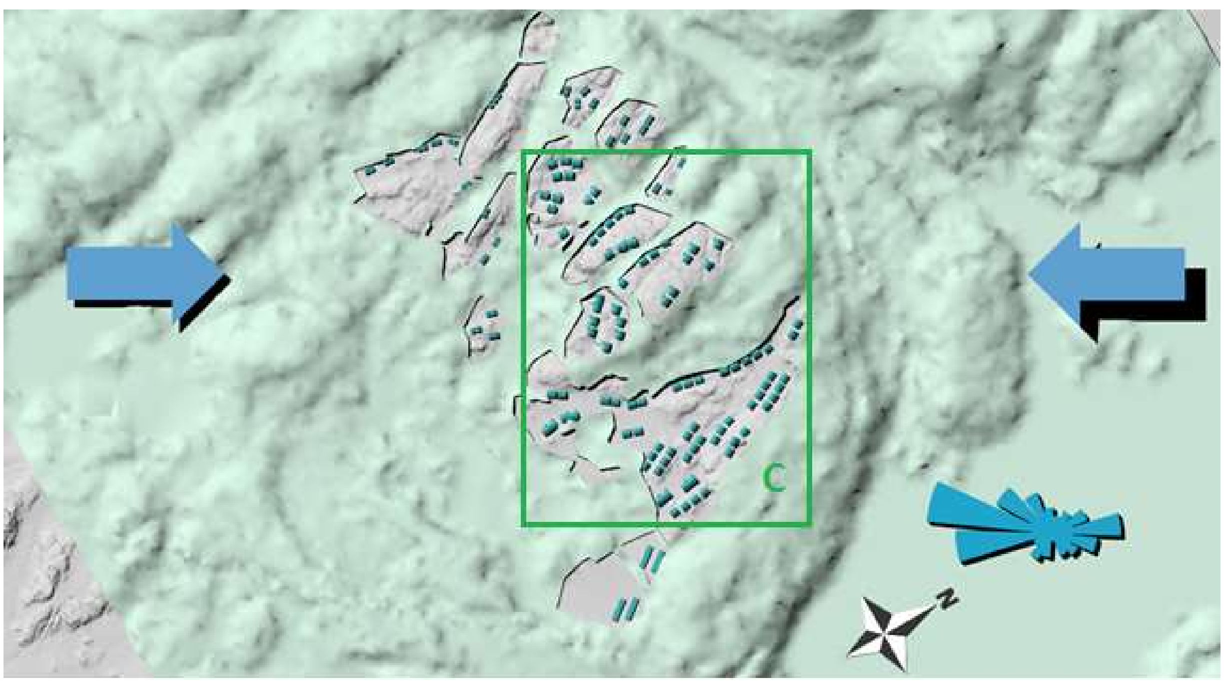

Figure 28. Proposed configuration of buildings, wind direction SSW

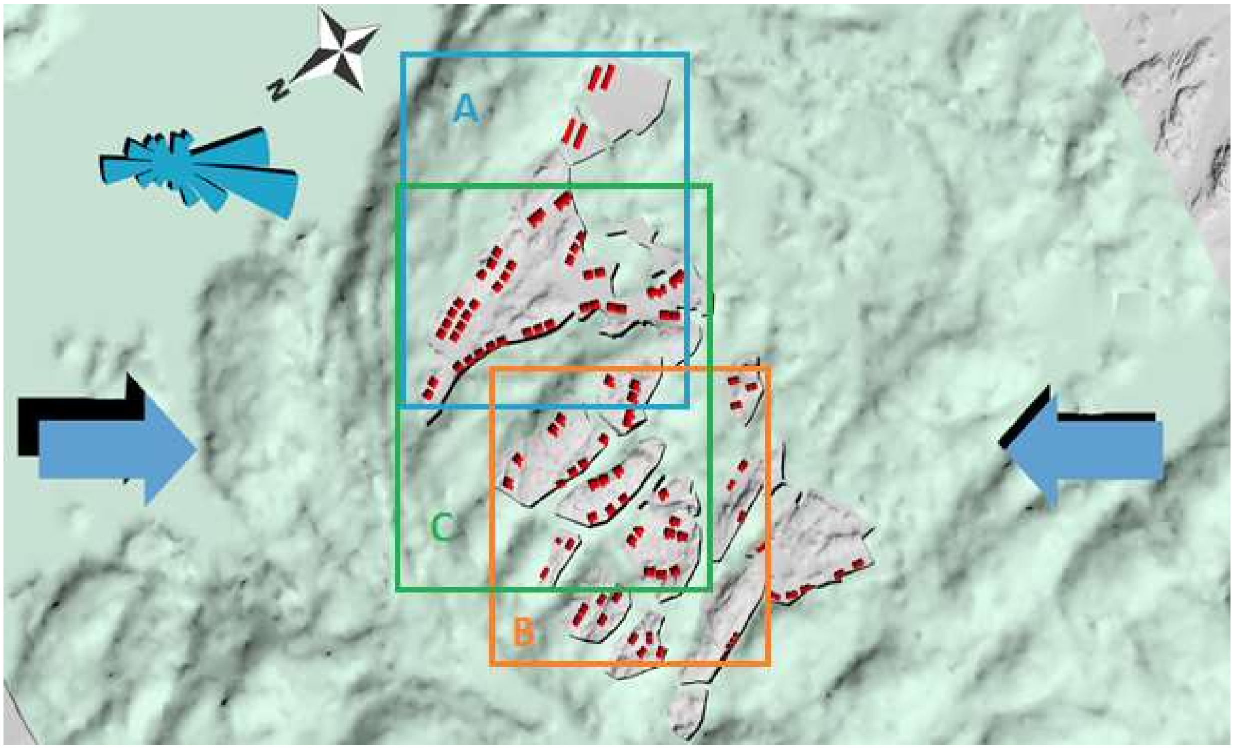

Figure 29. Original configuration of buildings, wind direction NNE

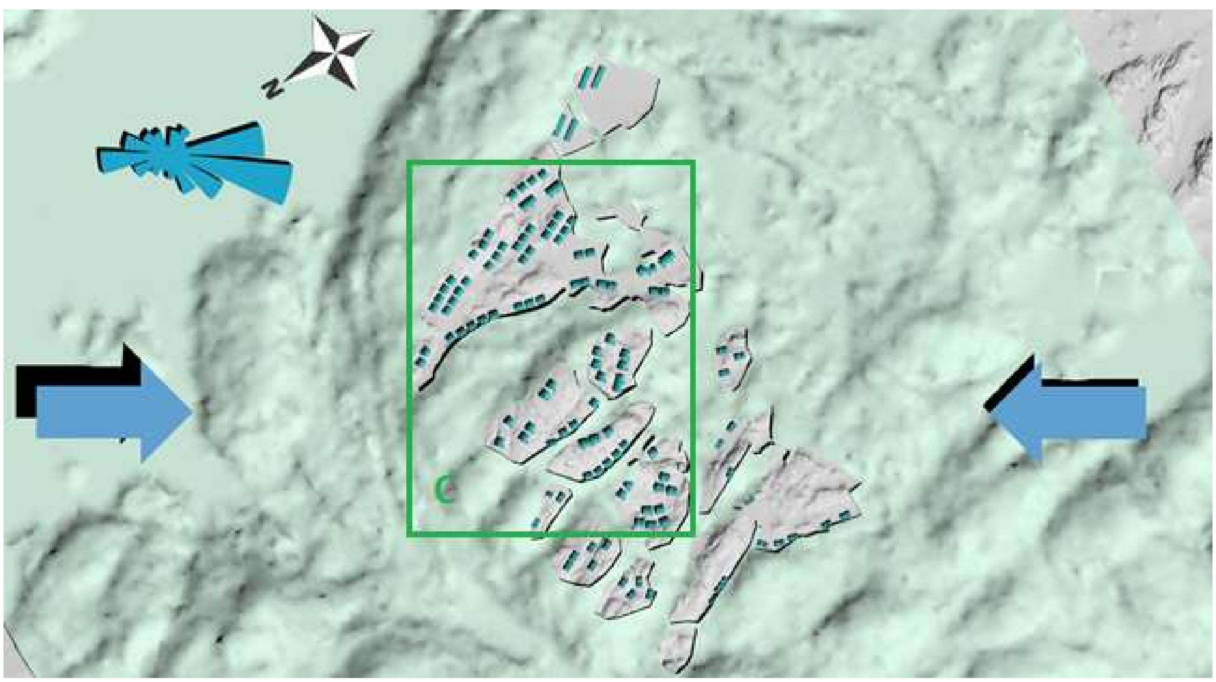

Figure 30. Proposed configuration of buildings, wind direction NNE

3.3 Numerical model

For the simulations, Flow 3D software has been used to simulate air flows. The Flow 3D is a Computational Fluid Dynamics (CFD) software, and is being developed by Flow Science Inc. Flow 3D is a Reynolds Averaged Navier-Stokes (RANS) solver, which solves Navier-Stokes equations numerically, (Rambøll Norge AS, 2016) using three-dimensional, finite difference methods and Eulerian particle model for the conservation of mass, impulse and momentum in volume-fluid in order to solve two-phase time-dependent problems (Sundsbø, 2013).Flow 3D uses Renormalized Group (RNG) k-ε turbulence model. CFD software makes it is possible to perform numerical analyzes using computational resources as opposed to model experiments in the wind tunnel.
Terrain and building model was imported for use in Flow 3D. The building and terrain models were created in Rhinoceros 3D software.
A simulation domain was created, using a number of elements in *x*, *y* and *z* directions. High number of elements provides greater accuracy, at the cost of increased demand for computational resources, and as a result – increased simulation time. To achieve a good level of accuracy, with acceptable simulation times, the mesh had to be adapted. A finer mesh with higher amount of elements was created in subdomains of particular interest, i.e. such as building locations. The rest of the simulation domain was filled with coarser mesh, with smaller amount of elements. The end "shape" of the mesh, when viewed in 2D roughly represents the "cross" pattern. Several simulations were performed based on the prevailing wind directions. For each simulation, the model was setup such that inflowing wind fields moves from the current wind direction. The inflowing wind field is based on 10-minute average wind speeds (Sundsbø, 2015). The vertical velocity distribution, roughness of the terrain and turbulence intensity are determined by the wind gradient effect (Sundsbø, 2015).
For input parameters in Flow 3D, following was considered. The wind speed in the simulations is set to 10 m/s constant, incompressible, irrotational flow. The inflowing wind has a logarithmic velocity profile, i.e. the wind speed is dependent on height and surface roughness, and it is increasing, according to the formula in eq. xx. The wind speed was chosen based on wind measurements at 10 meters altitude done at close terrain, though, ideally, the wind speed measurements should have been done on site. In addition, local vegetation, in the form of forest has a 0.5 porosity parameter and 0.4 drag coefficient. These values are based on scanning the nearby forested area from the helicopter.

Following simulations have been done in Flow 3D:

1. SSW wind direction with no buildings and cut down vegetation present.
2. SSW wind direction, with cut down vegetation and buildings present. Buildings were grouped into 3 subareas, denoted A, B and C. For each of them, separate simulation was done.
3. SSW wind direction, with cut down vegetation and building present. Compared to simulation 2, building locations have been adjusted, based on the results from previous simulations.
4. NNE wind direction with no buildings and cut down vegetation present.
5. NNE wind direction, with cut down vegetation and buildings present. Buildings were grouped into 3 subareas, denoted A, B and C. For each of them, separate simulation was done.

The main purpose for doing simulations with cut down vegetation and no building present is to understand the air flow behavior in this areas, that is based on the project plan provided by Larvik municipality. The simulations with building locations present, as specified in the development plan, and cut down vegetation, again, according to the development plan of Martineåsen area, corresponds to planned conditions in the area, when the construction project will be finished.

Subsequently, the next set of simulations is done, with modified building locations, based on the results from previous simulations. The simulations were done for SSW wind direction, as this direction, as it can be seen from wind rose in fig. 25, is the prevailing wind direction throughout the summer period. The wind direction NNE was chosen due to the prevailing wind direction throughout the winter period.

4. Results from numerical simulations

Results from numerical simulations of wind are presented in figures 32-40, as taken from Flow 3D. The color scale indicates wind speeds at the terrain level. The lowest wind speed is indicated as blue color and the high wind speed is indicated as red one. Wind arrows are placed to indicate current wind direction.
The figures show wind speeds using color scale. The scale goes from 1-7 m / s. The wind direction in simulations is south-southwest (SSW) direction, as it is prevailing wind direction throughout the year, and in summer, in particular.
Simulation results without buildings and cut down vegetation for SSW wind direction show that the highest wind speed will be expected at elevated terrain in the central zone of Martineåsen region. It means that buildings located there will be exposed to significant wind stress. Some additional areas with high magnitude of expected wind velocity are located at elevations, forming a "ring" around the central elevation. The lowest wind speed values are expected in lowland sections, located further away from the central elevation.

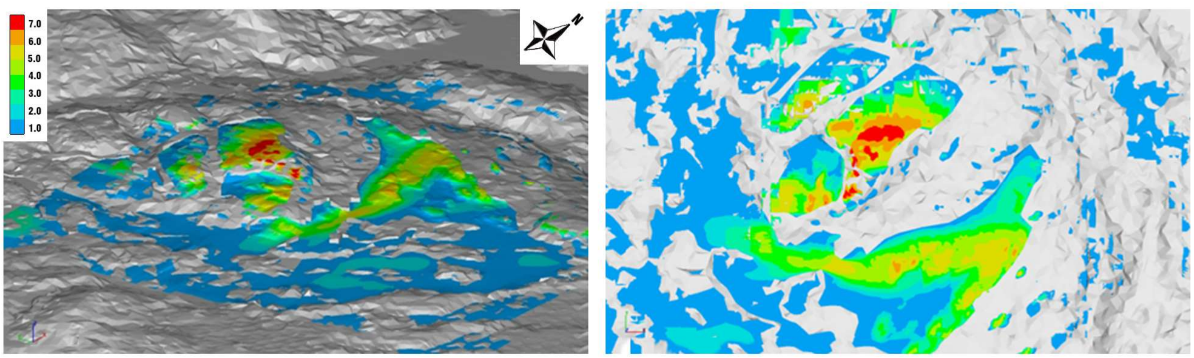

Figure 31. SSW wind direction simulation without buildings and cut down vegetation

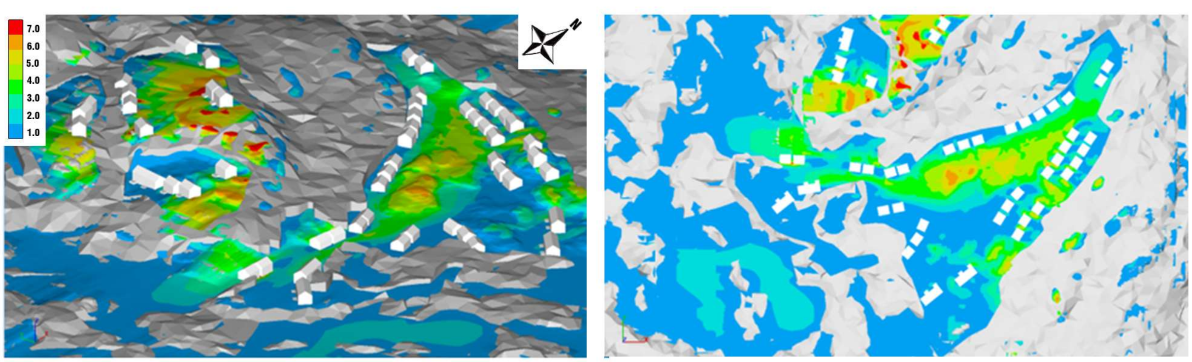

Figure 32. SSW wind direction simulation with buildings for area A

Simulation results for area A, given in fig. 33 show that the highest expected value of wind stress will be on elevated terrain, close to the center. The lowest wind speed will occur at lower elevations of area A and near the vegetation located in the western direction of area A, therefore, buildings situated near forest in the western direction of said area will have lowest values of expected wind stress, acting on them. There is an additional peak of high wind speeds, towards some hills in the eastern part of the area A, however, they are situated a short distance from the closest houses, and, in general, should not affect the wind stress values on nearby buildings by a significant amount.

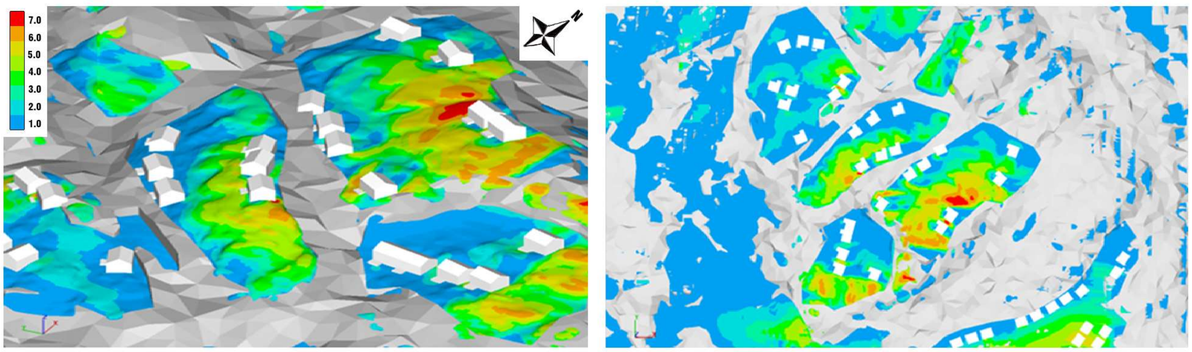

Figure 33. SSW wind direction simulation with buildings for area B

Figure 34 shows simulation results for area B, with highest wind speed located at central elevated terrain, both left and right from the location of central ridge. The lowest wind speeds will occur at flats, located to the north and south from the central elevation. Some buildings, situated along the central ridge, at the base of the elevation also show quite low values of affected wind speeds, and, as a result - wind stress on them will be generally low.

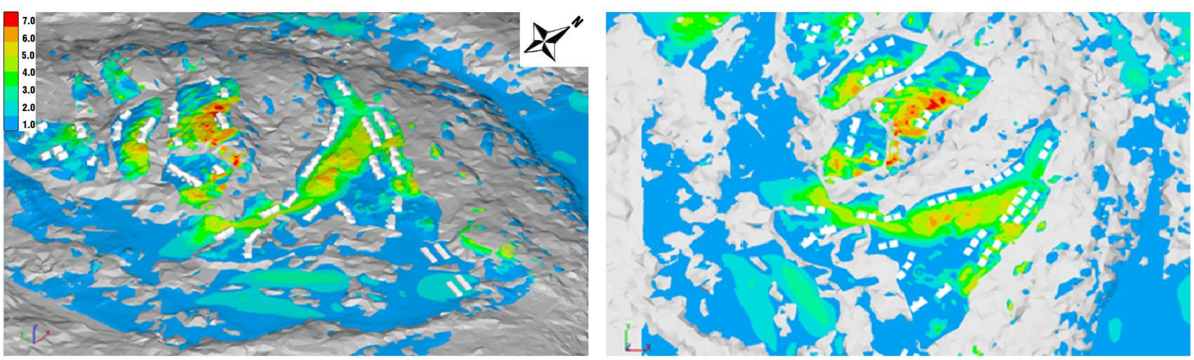

Figure 34. SSW wind direction simulation with buildings for area C

Based on the simulation results for area C the decision has been made to change the configuration of buildings, due to high expected magnitude if wind-induced stress, acting on some of them, in addition to placing down some additional buildings in lowland flat terrain in southeastern part of area A, and for area B, the new buildings are placed on the elevated terrain in the central and western regions of area B, as shown in the fig. 36 .

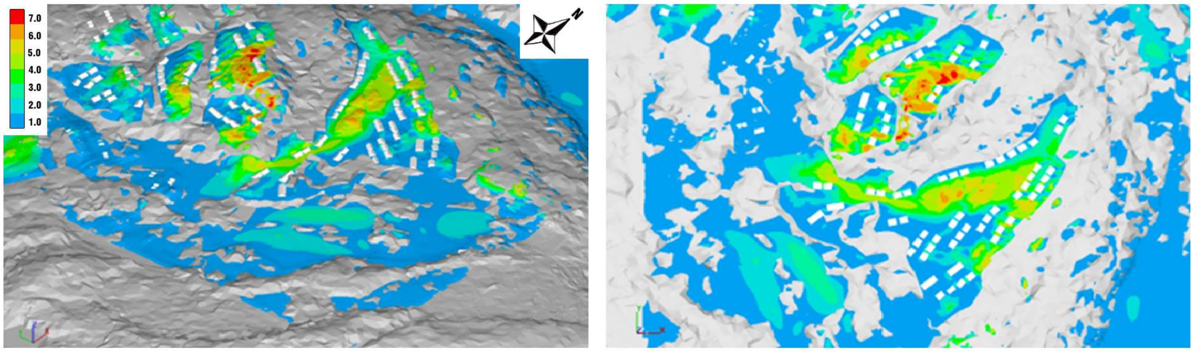

Figure 35. SSW wind direction simulation with buildings and new configuration for area C

Simulation results for terrain and cut down vegetation (no buildings) for the case of north-northeast (NNE) wind direction, are given in fig. 37. The NNE wind direction was used in simulations, as, according to the wind rose for winter period, given in fig. 25, the frequency of occurrence of NNE wind and its wind speed magnitudes are close enough to frequency of occurrence and wind speed magnitudes of SSW wind, which is the prevailing wind direction. The results show that elevated terrains in the area will experience the highest magnitude of wind speeds. In addition, the small basin, with relatively rough terrain, slightly to the north from the central elevation, which is subjected the most to the high wind speeds, will experience similar wind speed magnitudes. There is an additional high, located at rather steep slope, north-northeastern from central elevation. Consequently, the lowest wind speed will be experienced by area adjacent to the vegetation and in lowland areas, spanning through the project area, located to the east of central elevation.

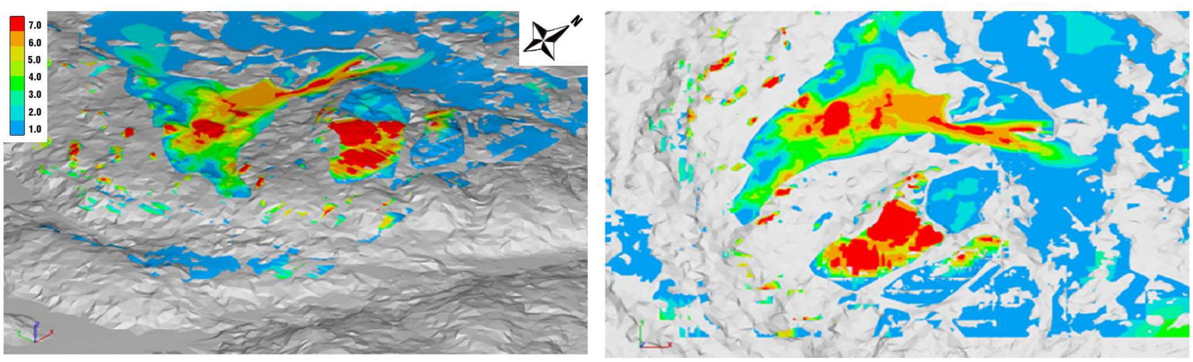

Figure 36. NNE wind direction simulation without buildings and cut down vegetation

There are a few locations, exposed to high wind speeds, in particular, - the rough central elevation, the small basin, directly to the east, the slope directly behind said basin, further east and some rough area in southern part of area A. The high wind speeds at central elevation can be somewhat ignored, to an extent, as there is no directly adjacent house to it, however, this is not the case for rest of locations, exposed to high wind speeds, in particular, the eastern areas. On the other side, the lowest wind speeds will be present in lowlands, to the west, north, and south-southeast, with respect to the central elevation.

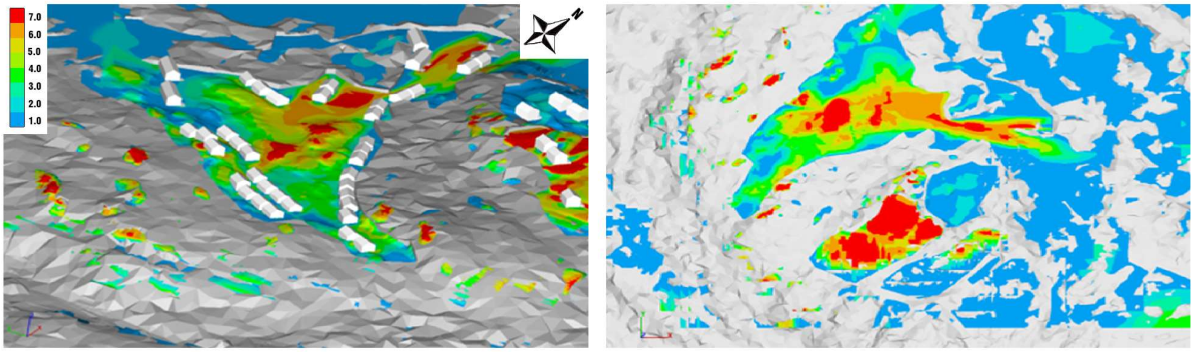

Figure 37. NNE wind direction simulation with buildings for area A

The highest wind speed for area B will be expected for the rough, elevated terrain in the western and southern direction. The southern region can be somewhat ignored, again, as there are no buildings present. Consequently, the lowest wind speed will be in the lowlands region in the northern and eastern-southeastern parts of area B.

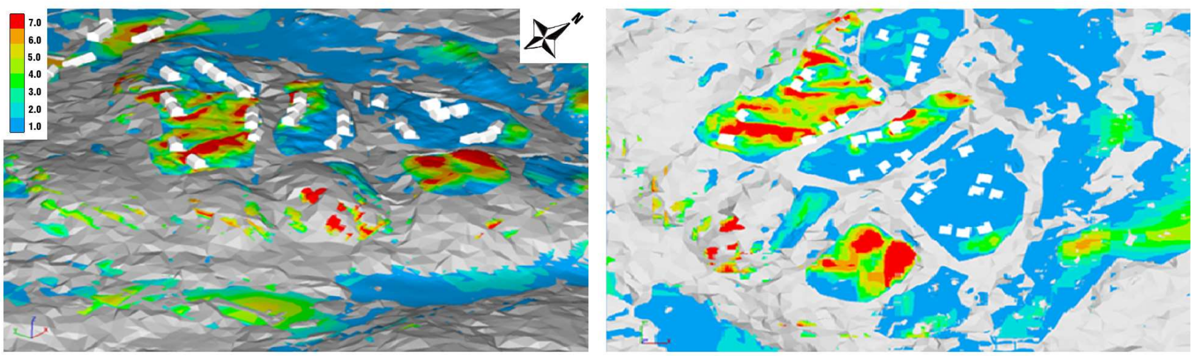

Figure 38. NNE wind direction simulation with buildings for area B

Based on previous simulation results for area A and B was decided to chose area C for wind simulation analysis in NNE wind direction with the same buildings configuration, as for are C for wind direction SSW. Simulation results, given in fig for area C with NNE wind direction show that the highest wind speed will be elevated terrain in southern direction and north-western direct, the lowest wind speed will be in the central and in the east zones of chosen area.

In addition, the entire project area, also referred as area C was simulated for NNE direction. Since area C consists of areas A and B combined, the same conclusion about maximum and minimum velocities apply here. The goal of simulation is to observe any significant differences between simulation results for area C and areas A and B. As it can be seen from figs. 38-40, the results of all simulations agree well. In general the wind effects are more pronounced for NNE wind direction than the corresponding results for SSW wind direction. This can be explained by general building alignment along the SSW wind directions

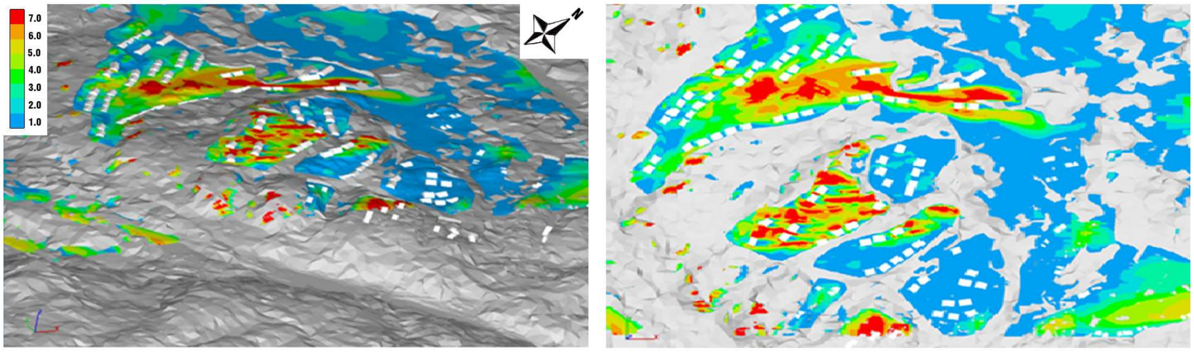

Figure 39. NNE wind direction simulation with buildings for area C

5. Local climate effect

Based on performed analysis of the Martineåsen development are in Larvik, the most important result is that the whole entire project area cannot be used for building purposes. The reason for it is that removing of local vegetation, according to development plans results in rather noticeable increase in wind effects on the exposed terrain. The situation is complicated by the fact that Martineåsen development area is situated in elevated and hilly terrain, which increase the impact of turbulence and wind speeds in the area further. This is an expected outcome, considering general theory of fluid dynamics and knowledge of local wind systems. The increase in developed wind effects can be significant enough that the planned area will not be usable under outdoor comfort activity criteria. This conclusion is mostly relevant for buildings, located at elevated parts of Martineåsen development area.

One possible solution is to relocate the exposed buildings towards flats and basins, which has been done in the new configuration. As the results for new configuration have shown, this reallocation allows to counter some of more pronounced local maxima in wind speeds, in addition, it is also possible to fit in additional buildings in the lowland parts of Martineåsen development area, thus partially countering the fact that not entire area can be used as planned. In addition, aligning the buildings along the prevailing wind direction shows that the wind effects on the buildings are reduced with this alignment. Simulation results for south-southwest (SSW) wind direction show lesser values in predicted wind speeds, as opposed to the north-northeast (NNE) direction, even though the exact same input parameters for wind conditions have been used in both simulation sets, with only difference being the wind direction. Moreover, the NNE wind direction in winter has almost matching frequency of occurrence and mean wind speeds, when compared to SSW direction, as evidenced by the wind rose. Therefore, additional study with NNE wind direction, for winter time is warranted, with further inclusion of impact of snowdrift on the infrastructure in winter period.

The Martineåsen project area is quite suitable for residential purposes, especially if wind conditions in basins and lowlands are taken advantage of. Furthermore, the block-type buildings, situated in area A, tend to perform best in simulation results. Whether or not this due to their locations in the development plan, this can be further taken advantage of, if the total population capacity in the area is of a concern, as judging by said plans, this type of buildings has higher residential capacity than other two. On the other side, single house with terraces tend to perform the worst, as it is evidenced by the results for areas A, B and C for the case of NNE direction. This is, again, an expected outcome, as terraces will serve as a sort of "stress concentrations" when it comes to wind effects, as was outlined in the theoretical background above. When it comes to single houses, according to development plans, these should primary be located at elevated locations throughout the Martineåsen project area. As indicated in development documents, this particular choice of building types is mostly aesthetical. If general aesthetics of the project area are of importance, some small adjustments to the building locations at elevated terrain can be done, in order to decrease the wind effects. As the simulation results show, there is sufficient capacity, in terms of area with more favorable locations to allow this sort of further modification.

Moreover, one way to decrease the developed wind effects will be in not cutting the whole vegetation down, as the forest regions will, in general, slow the air flow in close vicinity. Thus, the strategic placement of green areas can help in reducing overall wind effects in entire Martineåsen development area, in addition to contributing to overall comfort and aesthetics of the area. For example, leaving the vegetation in locations of highest elevated terrain and hills may contribute to overall better distribution of wind effects in adjacent basins and slopes. Furthermore, the vegetation can be left in places, where some of the reallocated houses were located. Doing so will improve the wind effect situations of adjacent buildings.

For the purpose of further project development and additional CFD simulations on the wind effects, it might be beneficial to convey the present simulation results to the representatives of Larvik municipality council. The main gain of cooperation in this field, is the possibility to discuss further building sites placement alteration, both from the viewpoint of planned vision for the area and CFD results. These further modifications can potentially yield close to ideal placement of the buildings in the project area. The process here is iterative, as quite a significant number of building locations, building types and vegetation spots may be altered during the course of this cooperation, thus requiring quite a few development plan revisions and CFD simulations.

6. Conclusions

Throughout this master thesis work the climate effects for Martineåsen development project in Larvik were studied. The investigation started with establishing the background theoretical knowledge in the fields of fluid mechanics and climate effects, both on global and local scale. Following the theoretical investigation, the Computational Fluid Dynamics simulations were performed, based on measured meteorological data for Larvik, in addition to some measurements of wind speed, done at close terrain and vegetation scanning. This, coupled with the project development plans allowed to conduct necessary simulations of wind effects on the Martineåsen project area site, with local topography and conditions properly accounted for.

Based on simulation results, it was found that the original plan for building layout is not ideal. At least some of the building locations are situated in such locations, where wind conditions would not make outdoors stay comfortable. Moreover, it was established that the removal of local vegetation, in the form of the forest at Martineåsen amplifies the wind effects by a large amount, as natural vegetation serves as sort of a "dampener" to the turbulence and rough terrain effects. Without said forest, the area is exposed to the wind, especially in a rough terrain, at the hills. As a result, the Martineåsen project area cannot be used in its entirety.

To overcome this obstacles, some of the original building locations were modified, by placing the buildings in regions with more favorable conditions. Furthermore, it was found out that the building count could be increased, especially in lowlands regions of Martineåsen area. This information can be useful in the future simulations and to discuss possible modifications to the present project development plans with representatives of Larvik municipality. In addition, simulations with an updated building configurations were run with NNE wind direction, in addition to simulations with SSW wind direction, which is the prevailing wind direction on the site. The results suggest, that aligning the buildings with respect to prevailing wind direction has a positive impact on the wind effects, experienced by buildings. However, since NNE wind direction is roughly as frequent in winter time as SSW, additional simulations for these particular conditions might be warranted, in addition to studying possible effect of snowdrift on the local infrastructure.

Therefore, the ideal continuation of present work is to discuss possible project plans alterations with Larvik municipality representatives. These alterations should affect the building placement layout, building types and vegetation layout. It is deemed, that following interactive process of updating development plans and performing the CFD simulations, according to these plans may result in a significantly improved layout in the end, which is beneficial Martineåsen development project. Moreover, it is deemed necessary to perform some studies on wind shielding concepts, in particular, possible usage of building layout and local vegetation as wind shielding measures.

Referances

Asplan, V. (2017, 05 01). *Brøset Lokalklimaanalyse*. Hentet fra file:///C:/Users/msh018.AD.001/Downloads/Lokalklimaanalyse%20BrÃ¸set%202010%2010%2029%20med%20vedlegg.pdf

Bjerg, S. (2012). *Wind environment in the architecture.* Hentet fra http://www.re-ad.dk/ws/files/39545731/Vind.pdf

Børve, A. (1987). *House and house groups in climate change, cold regions: design and functioning.* Oslo: Oslo Academy of Architectural Sciences.

Brennen, C. E. (2017, 04 20). *Fundamentals of Multiphase Flows*. Hentet fra http://authors.library.caltech.edu/25021/2/cabook.pdf

Çengel, Y. &. (2011). *Heat and Mass Transfer: Fundamentals and Applications.* New York: McGraw-Hill Education.

classification, K. m. (u.d.). Hentet fra https://commons.wikimedia.org/wiki/File:Norway_koppen.svg.

classification, K.-G. c. (2017). *https://commons.wikimedia.org/wiki/File:Norway_koppen.svg*.

DNMI. (2017, 12 03). *Climate data*. Hentet fra https://www.met.no/nyhetsarkiv/var-tjeneste-eklima-har-begrenset-tilgang

Dorf, R. C. (2017, 04 15). *The Engineering Handbook, Second Edition.* New Yourk: CRC-Press.

Dyrbye, C. &. (1989). *Wind load on load bearing structures.* Hørsholm: National Building Research Institute.

Fefferman, C. L. (2017, 04 27). *Existence and smoothness of the Navier-Stokes equation*. Hentet fra http://www.claymath.org/sites/default/files/navierstokes.pdf

Gabler, N. B. (2010). *US National library of medicine.* Hentet fra HSR Health service research: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC2813449/

Givoni, B. (1998). Climate Consideration in Building and Urban Design. *Van Nostrand Reinhold*, 244-296. Hentet fra http://www.cpas-egypt.com/pdf/AmalEldeberky/Research's/004%20%20%20The%20Influence%20of%20High-rise%20building%20and%20environment.pdf

Granger, R. (1995). *Fluid Mechanics.* New York: Dover publications, Inc.

Hacisevki. (2017, 03 27). *Internal Flow*. Hentet fra http://opencourses.emu.edu.tr/pluginfile.php/4503/mod_resource/content/1/Chapter8.pdf

Hanssen-Bauer, H. H. (2017, 05 1). *Mye vaer og mye vann*. Hentet fra http://www.cicero.uio.no/no/posts/klima/mye-vaer-og-mye-vann

Herman. (2017, 03 15). *Newton's Law of Viscosity, Newtonian and Non-Newtonian Fluids*. Hentet fra https://link.springer.com/referenceworkentry/10.1007%2F978-0-387-92897-5_143#page-1

Herman, F. (2017, 03 15). *Newton's Law of Viscosity, Newtonian and Non-Newtonian Fluids*. Hentet fra https://link.springer.com/referenceworkentry/10.1007%2F978-0-387-92897-5_143#page-1

Herman, G. (2017, 03 15). *Newton's Law of Viscosity, Newtonian and Non-Newtonian Fluids*. Hentet fra https://link.springer.com/referenceworkentry/10.1007%2F978-0-387-92897-5_143#page-1

Houlberg, C. (1979). *Wind and shelter in buildings.* Copenhagen: The Royal Danish Academy of Fine Arts, Building Technical Study Library.

Houlberg, C. (1979). *Wind and shelter in settlements.* Copenhagen: The Royal Danish Art Academy.

Huang, J. M. (2014). *Contributions of the Hadley and Ferrel Circulations to the Energetics of the Atmosphere over the Past 32 Years.* Cambridge: American meteorological society.

Kushnir, Y., & Stein, M. (2010). North Atlantic influence on 19th - 20th century rainfall in the Dead Sea watershed, teleconnections with the Sahel, and implication for Holocene climate fluctuations. *Quaternary Science Reviews*, 3843-3860.

Likavcan. (2017, 03 25). *Determination of apparent aiscosity* . Hentet fra http://www.ijeit.com/Vol%204/Issue%205/IJEIT1412201411_05.pdf

Marshall, C. E. (2001). *On the Dynamics of Wind-Driven Circumpolar Currents.* JOURNAL OF PHYSICAL OCEANOGRAPHY.

Meteorological institute . (2009). Hentet fra Bernoulli effect: https://metlex.met.no/wiki/Bernoulli-effekten

Meteorological institute. (2017). *Weather in Norway.* Oslo: Climate.

Munson, O. H. (2013). *Fundamentals of fluid mechanics.* Jefferson city: ISBN 978-1-118-11613-5.

Naylor, W. (2017, 05 20). *Wind chill and the wind chill index*. Hentet fra https://www.brentaski.com/blog/Wind%20Chill%20and%20the%20Wind%20Chill%20Index.pdf

Puttkammer. (2017, 04 5). *Boundary layer over a flat plate*. Hentet fra file:///C:/Users/msh018.AD.001/Downloads/BSc_report_Peter_Puttkammer.pdf

Qian Y, Z. J. (2015). *Alpers disease mutations in human DNA polymerase gamma cause catalytic defects in mitochondrial DNA replication by distinct mechanisms.* Hentet fra Frontiers in genetics: http://journal.frontiersin.org/article/10.3389/fgene.2015.00135/full

R.W.Johnson. (2017, 04 10). *The Handbook of Fluid Dynamics*. Hentet fra https://doi.org/10.1201/b19031-3

Ramstad, K. E. (2014). *Wood buildings.* Oslo: SINTEF Academic publisher.

Roylance, D. (2017, 03 14). *Mechanical properties of materials*. Hentet fra http://web.mit.edu/course/3/3.225/book.pdf

Simon. (2017, 04 10). *Introductory fluid mechanics*. Hentet fra http://www.macs.hw.ac.uk/~simonm/fluidsnotes.pdf

SINTEF Building Research. (2003). *471.043 Wind loads on buildings.* Hentet fra Http://bks.byggforsk.no/DocumentView.aspx?sectionId=2&documentId=3118

Thiis-Evensen, T. (2007). *Europe's architecture history from idea to form.* Oslo: Gyldendal Norwegian publishing house.

Thue, J. (2014). *Building Physics - Foundation.* Trondheim: NTNU.

Utaaker, K. (1991). *Micro and local meteorology.* Bergen: Alma Mater Forlag AS.

Vindteknikk, K. (2017, 05 15). *Effects on local wind climate for the construction of high-rise buildings*. Hentet fra https://www.sandnes.kommune.no/Fillager/Internett/resultaterheter/plan/Kunngjoringer/Godkjent/2013102/15% 20Vindanalyse .PDF

Yunus A. Çengel, J. M. (2006). *Fluid Mechanics: Fundamentals and Applications.* ISBN 0–07–247236–7.

Appendix A –Master thesis assignment

Faculty of Engineering Science and Technology
Master programme of Engineering Design

MASTER'S THESIS

for

Maria Shunina (501328)

Spring of 2017

Analysis of local climate effects for Martineåsen development project in Larvik

(Lokalklimaanalyse for utbyggingsprosjekt)

This document is the formal assignment and task description for a master's thesis project at University of Tromsø (UiT). The master's thesis project may be given in collaborating with industry partner or external research institute.

Changes may be done with respect to the content end extent of the project. The given title of this master thesis project is to be regarded as a working title and may be slightly change during this project. However, such changes should be discussed with all parties and must be approved by the main supervisor at the UiT.

Project background

The local municipality is responsible for plan for land use in Norway and land planning to ensure adherence to building codes and standards is the Technical Regulations under the Norwegian Planning and Building Act (PBA). The regulations have been performance-based since 1997. In general design requirements for outdoor activity areas are governed by human comfort criteria and safety issues. The design requirements are functionality requirements depending on type activity and further application. The Norwegian building regulations requires that all outdoor activity areas in general must be planned and developed in order to fulfil the given functionality requirements. Outdoor comfort in northern regions is mainly controlled by wind and consequently the outdoor activity areas must be sufficient shielded. Development of wind shielding measures and planning for comfortable sheltered outdoor areas is often referred to as Wind Control.

Favourable site selection forms the basis for all traditional settlements. People carefully selected sites that were naturally sheltered or least exposed to strong winds and blowing snow. Traditional villages in windy parts of Norway were always located in naturally sheltered zones. Now, the most sheltered locations for buildings are occupied which usually leaves us with few optional sites.

Larvik municipal is developing green areas in Martineåsen for residential and other purposes. This includes clearing of forest which will create wind exposed zones in a rather hilly terrain. For the land planning, it is therefore important analysis the local effects of removing trees for development settlements and infrastructure. In particular, the sections of the highest hills may be very exposed to wind.

Problem description

This master project includes performing an analysis of local climate effects for Martineåsen development project in Larvik. The analysis will focus on wind- and wind related effects on the outdoor environment. The analysis should include, and relate to the ongoing municipal land planning process directed by guidelines given by the Larvik municipal project group.

Main objectives

1. Perform an analysis of local climate effects for Martineåsen development project in Larvik.
2. Develop more understanding & knowledge about wind conditions in outdoor areas and effects of clearing forest for land planning purposes.
3. Develop more understanding & knowledge outdoor comfort
4. Suggest favourable design and location of buildings and evaluate alternative applicable wind shielding concepts that may be implemented in the ongoing development projects

Project description - Content

This master thesis should include:

- **Preliminary work/literature study related to actual topic**
  - State of the art study (best practice, knowledge areas etc.)
  - Legal framework, building codes and standards & guidelines (briefly)
  - Wind dynamics (local wind, climate; wind effects around buildings, structures and in terrain)
  - Wind effects on outdoor activity (human comfort, wind danger & wind induced weather exposure)
  - Review of wind shielding methods, application & techniques (shielding measures etc.)
  - Wind climate assessment (wind engineering, wind modelling & analysis)
  - Design criteria (specifications, constraints & requirements)
  - Environmental issues
  - Limitations and extent of project (methods applied, cases subject to analysis etc.)
  - Estimated time schedule for the project
- Design considerations related to environment, aesthetic & architectural style (arrange & present)
- Classification of wind shielding measures from application & functionality (arrange, evaluate & pres.)
- Numerical analysis of local wind effects related to existing situation and development concept with removal of trees. Analyse and suggest possible improvements.
- Numerical analysis of local wind effects related to buildings.
- Suggest and analyse possible wind shielding measures for outdoor activity areas.
- Eventual experimental work (wind shielding test case)
- Suggestion for future work/development

Preliminary work/literature study

After the task description has been distributed to the candidate a preliminary study should be completed within 4 weeks. The preliminary study may be submitted as a separate report or "natural" incorporated in the main thesis report. A plan of progress and a deviation report (gap report) can be added as an appendix to the thesis.

In any case the preliminary study report/part must be accepted by the supervisor before the student can continue with the rest of the master thesis. In the evaluation of this thesis emphasis will be placed on the thorough documentation of the work performed.

General Format Instructions

The thesis should be submitted as a complete research report and should include the following parts; Abstract, Introduction, Material & Methods, Results & Discussion, Conclusions, Acknowledgements, Bibliography, References and Appendices. Choices should be well documented with evidence, references, or logical arguments.

The candidate should in this thesis strive to make the report survey-able, testable, accessible, well written, and documented.

Materials which are developed during the master project such as software/codes or physical equipment, are considered to be documentation, a part of the master thesis (report). Documentation for correct use of such information should be added as far as possible, to the master thesis (report).

The Master's thesis project description (this document) must be added as an appendix to the thesis.

The report (Abstract, Introduction, Material & Methods, Results & Discussion, Conclusions, Acknowledgements, Bibliography, References) should **not exceed 50 pages**. Any additional material should be included in the appendix.

General project requirements

If the tasks or the problems are performed in close cooperation with an external company, the candidate should follow the guidelines or other directives given by the management of the company. The candidate does not have the authority to enter or access external companies' information system, production equipment or likewise. If such should be necessary for solving the task in a satisfactory way a detailed permission should be given by the management in the company before any action are made.

Any travel cost, printing and phone cost must be covered by the candidate themselves, if and only if, this is not covered by an agreement between the candidate and the management in the enterprises.

If the candidate enters some unexpected problems or challenges during the work with the tasks and these will cause changes to the work plan, it should be addressed to the supervisor at the UiT Campus Narvik or the person which is responsible, without any delay in time.

The level of classification must be addressed prior to distribution of the eventually sensitive material and the level of classification must be clear and marked on the thesis & belonging material.

The final report with its appendices must be submitted on MUNIN.

Date of distributing the task:	09.02.2017
Date for submission (deadline):	22.06.2017

Supervisor at the UiT Campus Narvik — Professor Per-Arne Sundsbø, Dr. Ing.
Phone: (+47) 769 66257 / 92 46 34 30
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Fjellveien 33, 8516 Narvik
Phone: (+47) 94865207
e-mail: marshu89@gmail.com / msh018@student.uit.no

Appendix B - Configurations of buildings

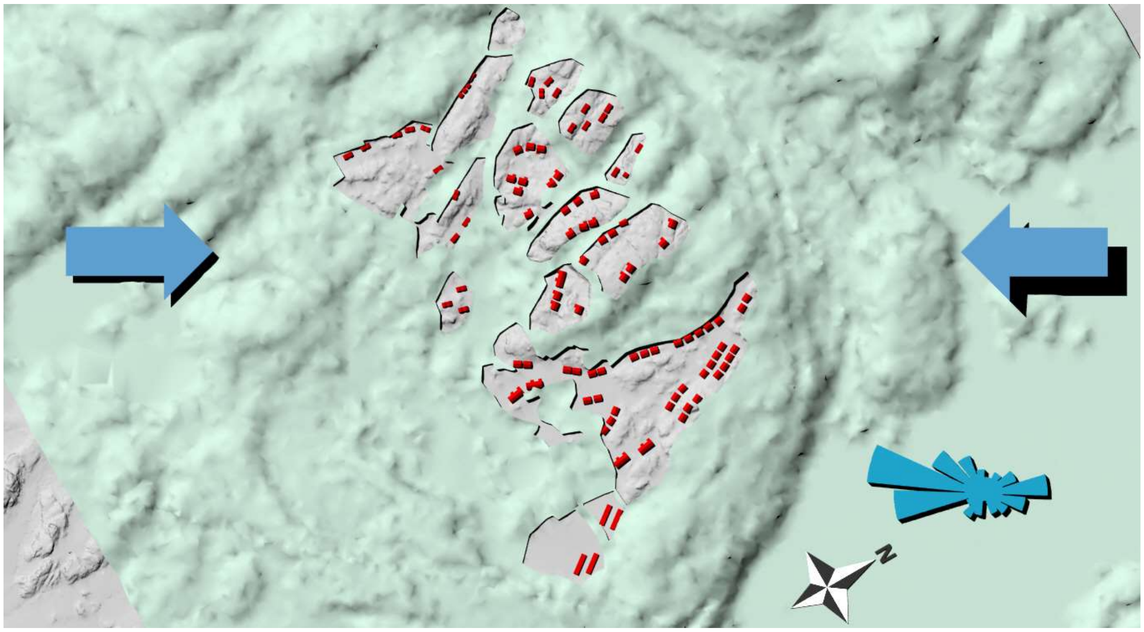

Figure 1. Original configuration of buildings, wind direction SSW

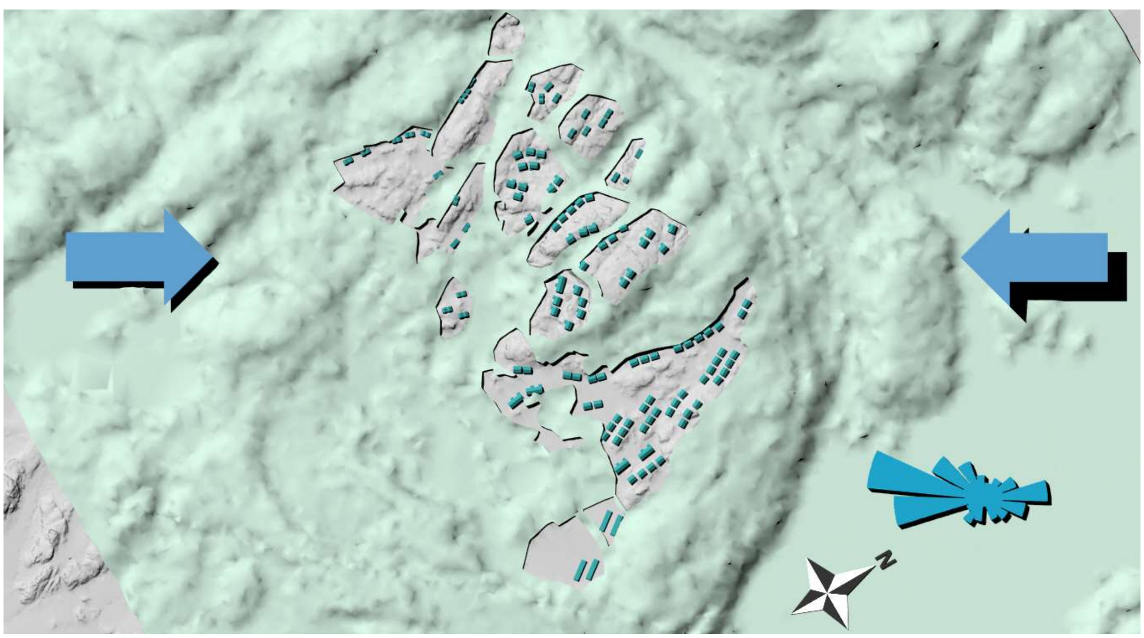

Figure 2 Proposed configuration of buildings SSV

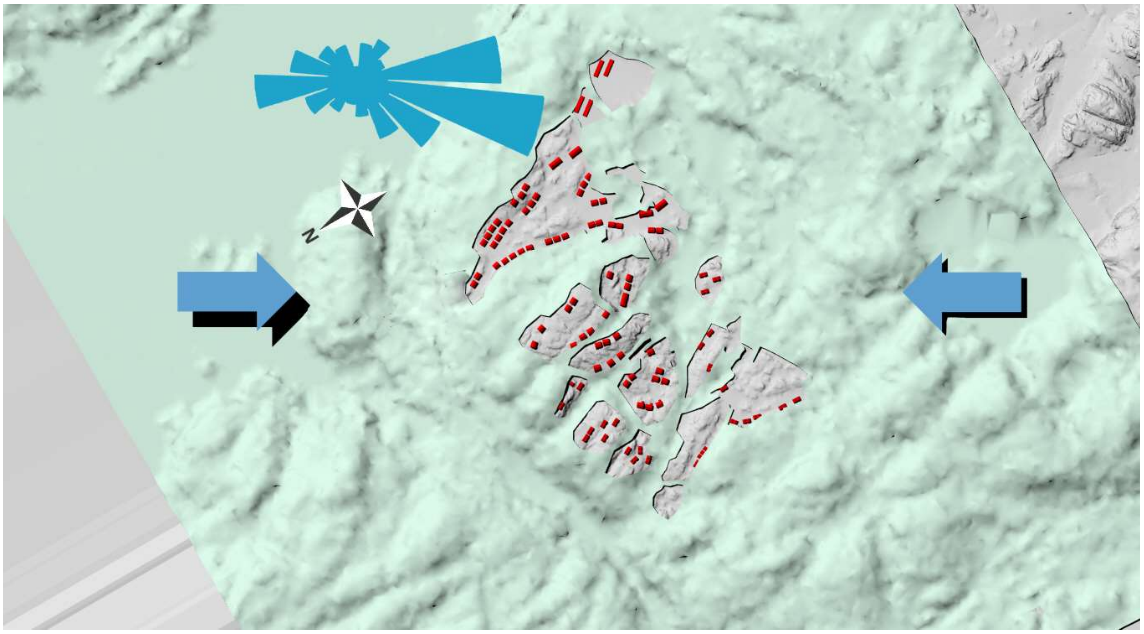

Figure 3. Original configuration of buildings, wind direction NNE

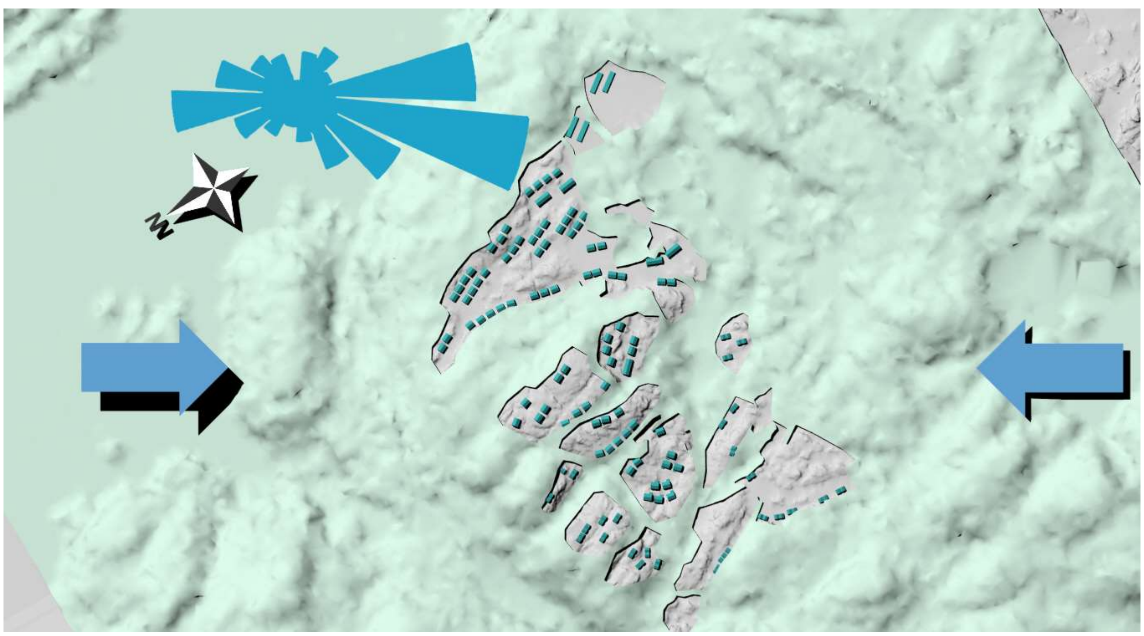

Figure 4. Proposed configuration of buildings NNE

Appendix C - Simulation results

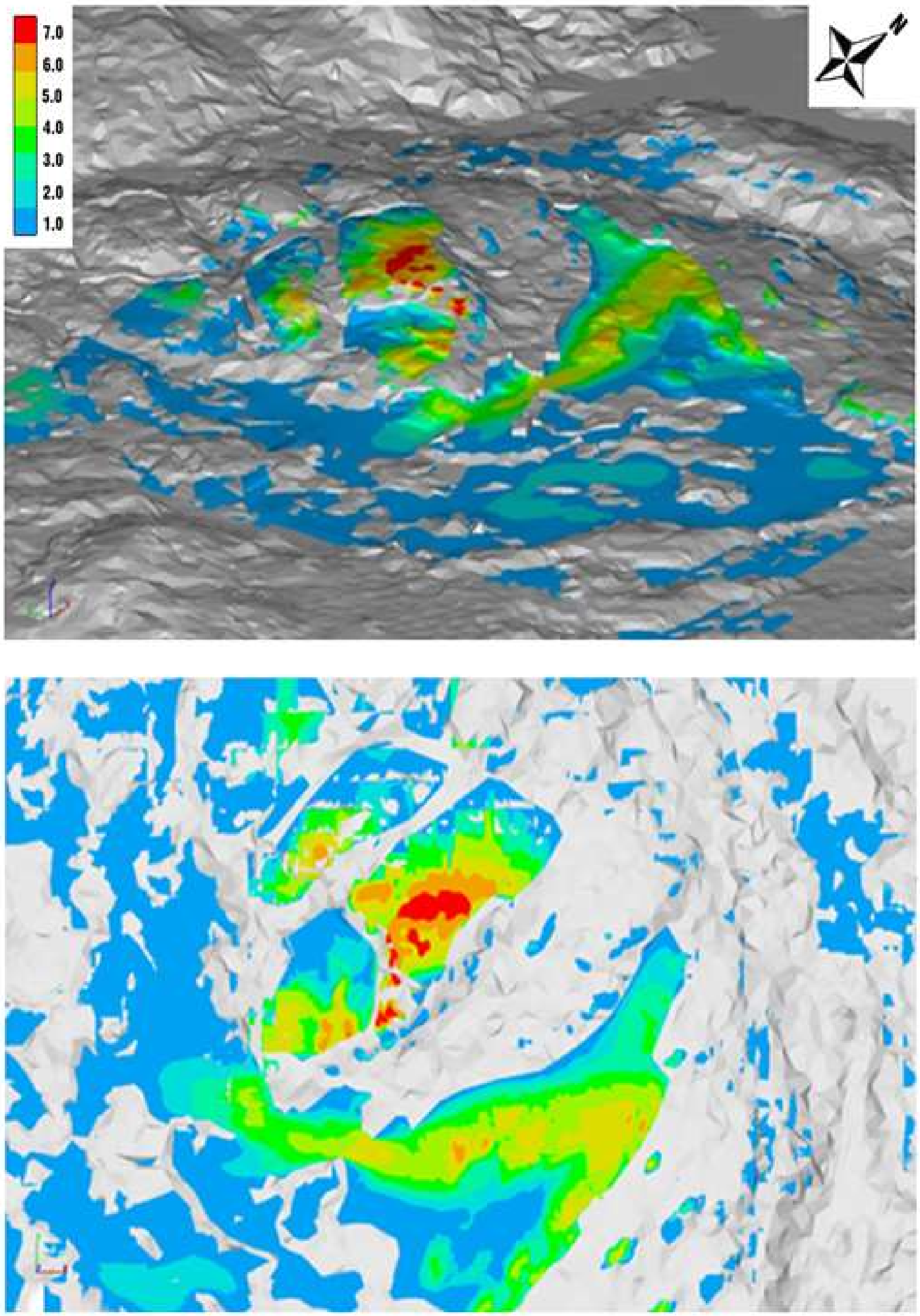

Figure 1. SSW wind direction simulation without buildings and cut down vegetation

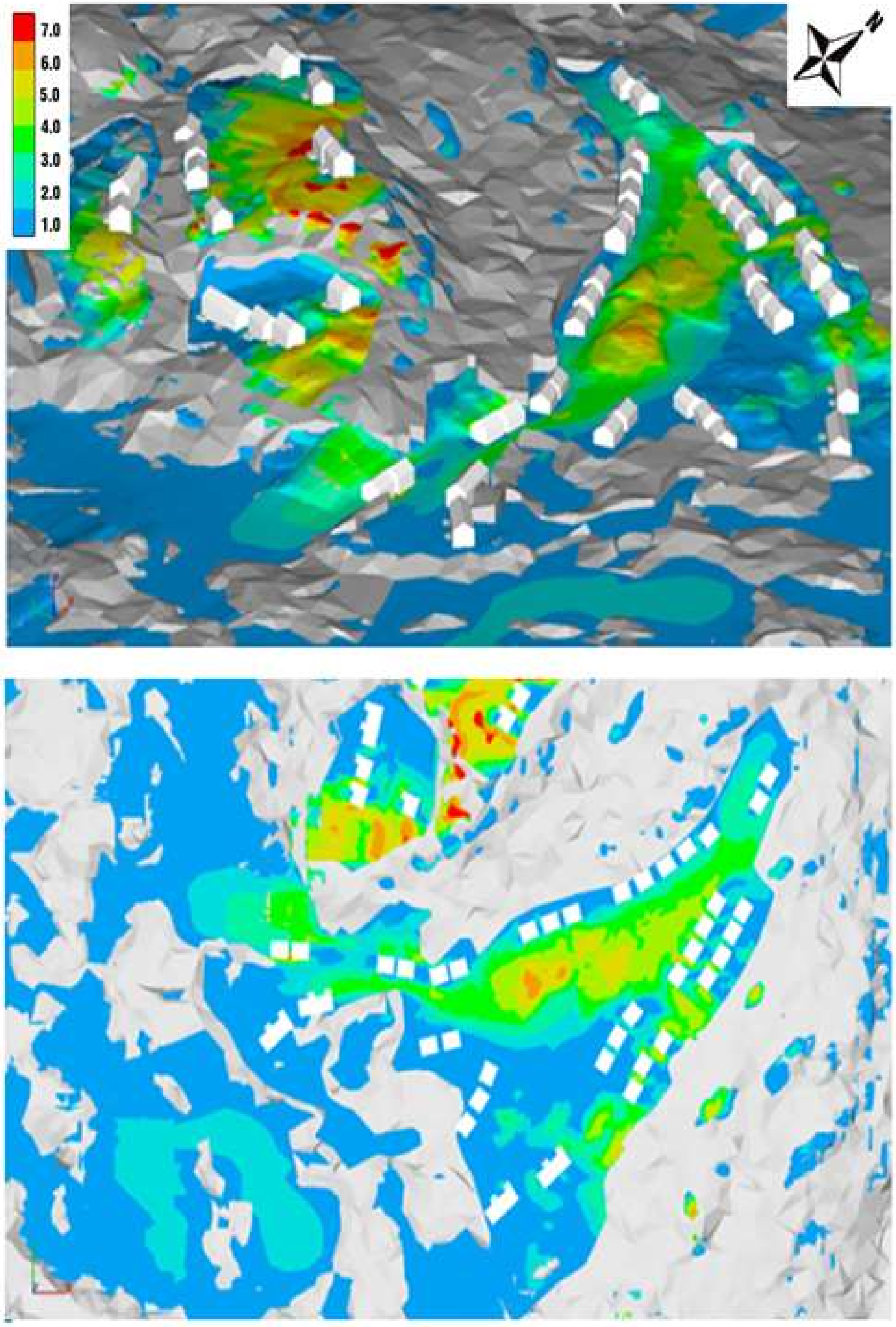

Figure 2. SSW wind direction simulation with buildings for area A

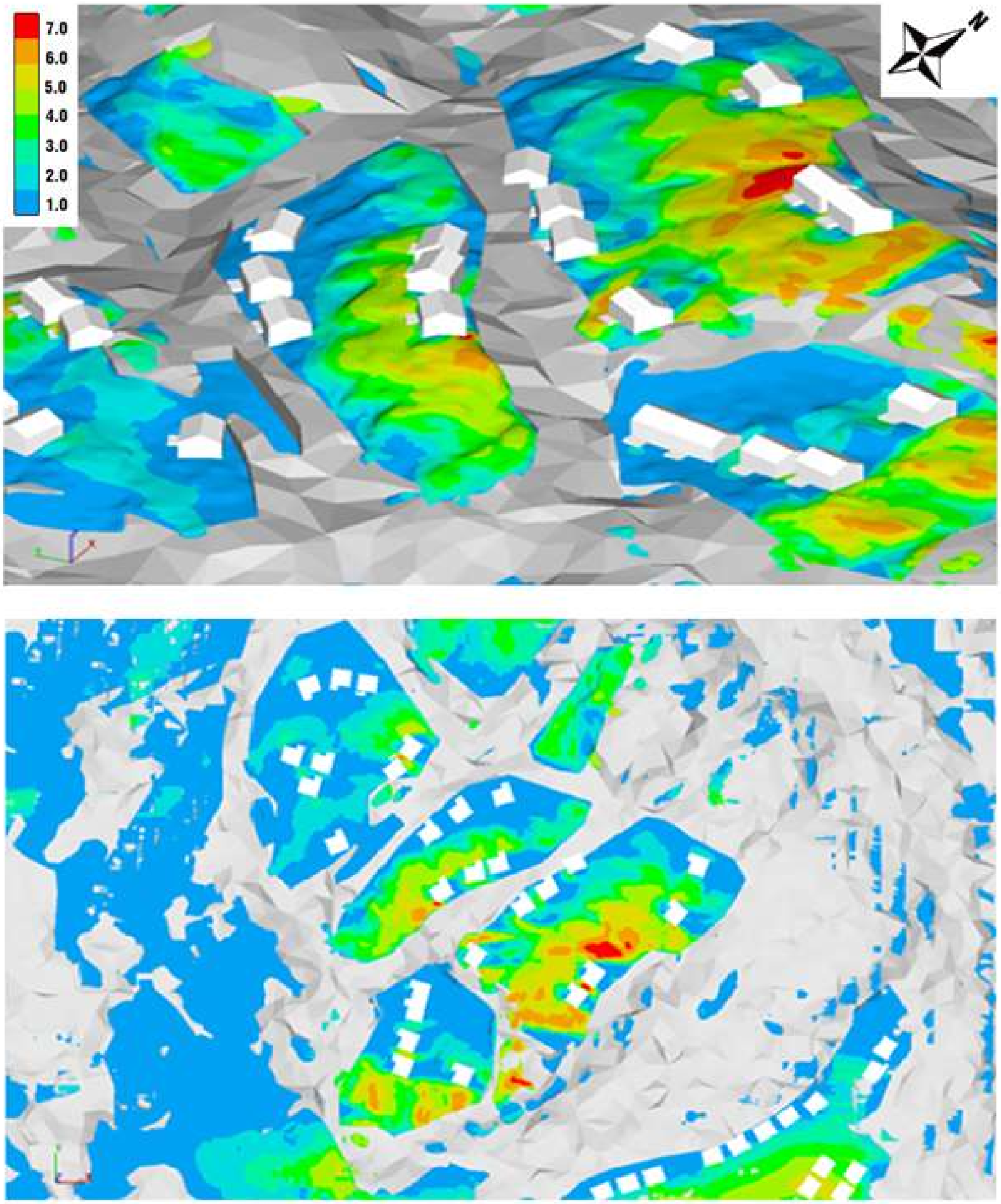

Figure 3. SSW wind direction simulation with buildings for area B

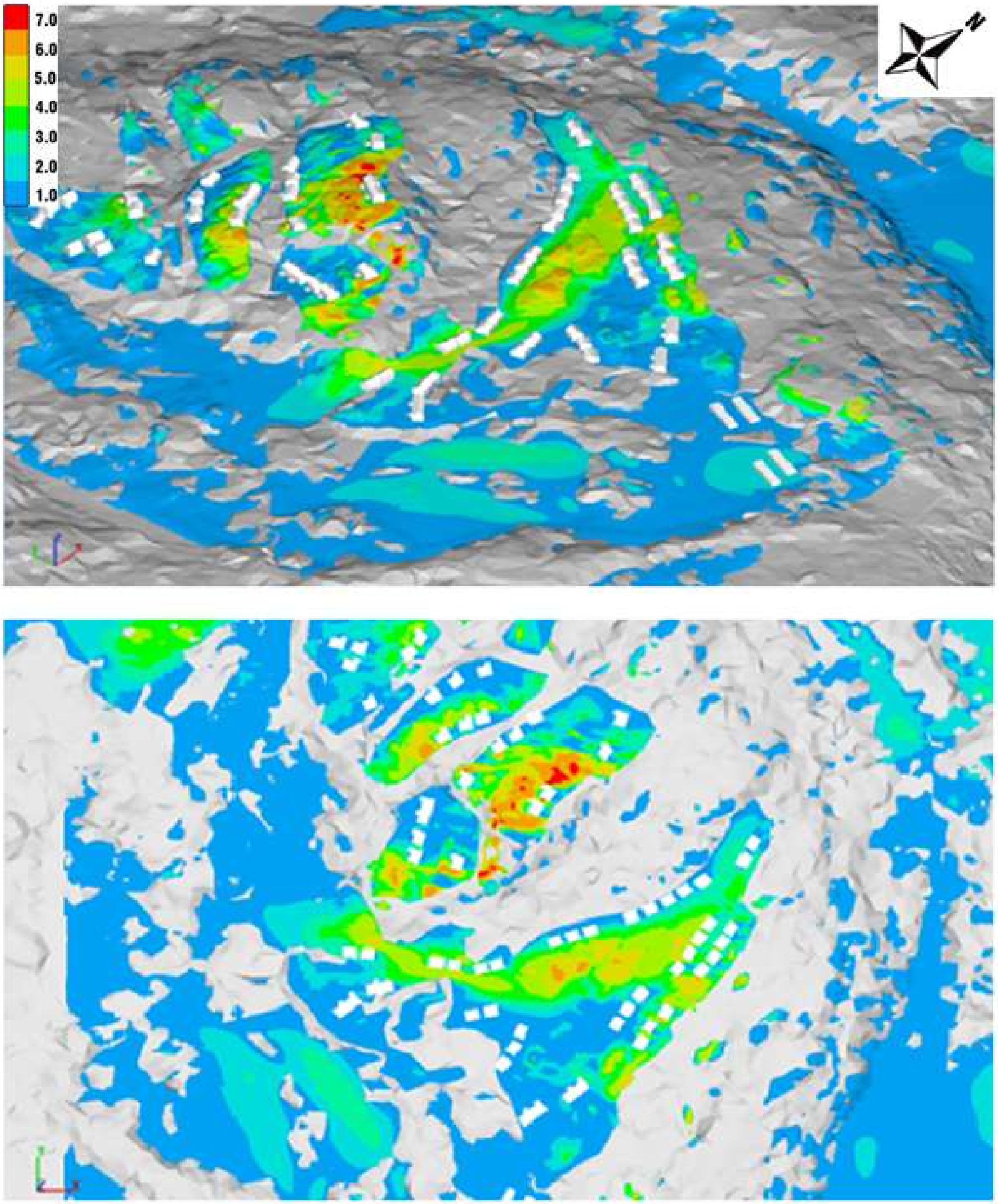

Figure 4. SSW wind direction simulation with buildings for area C

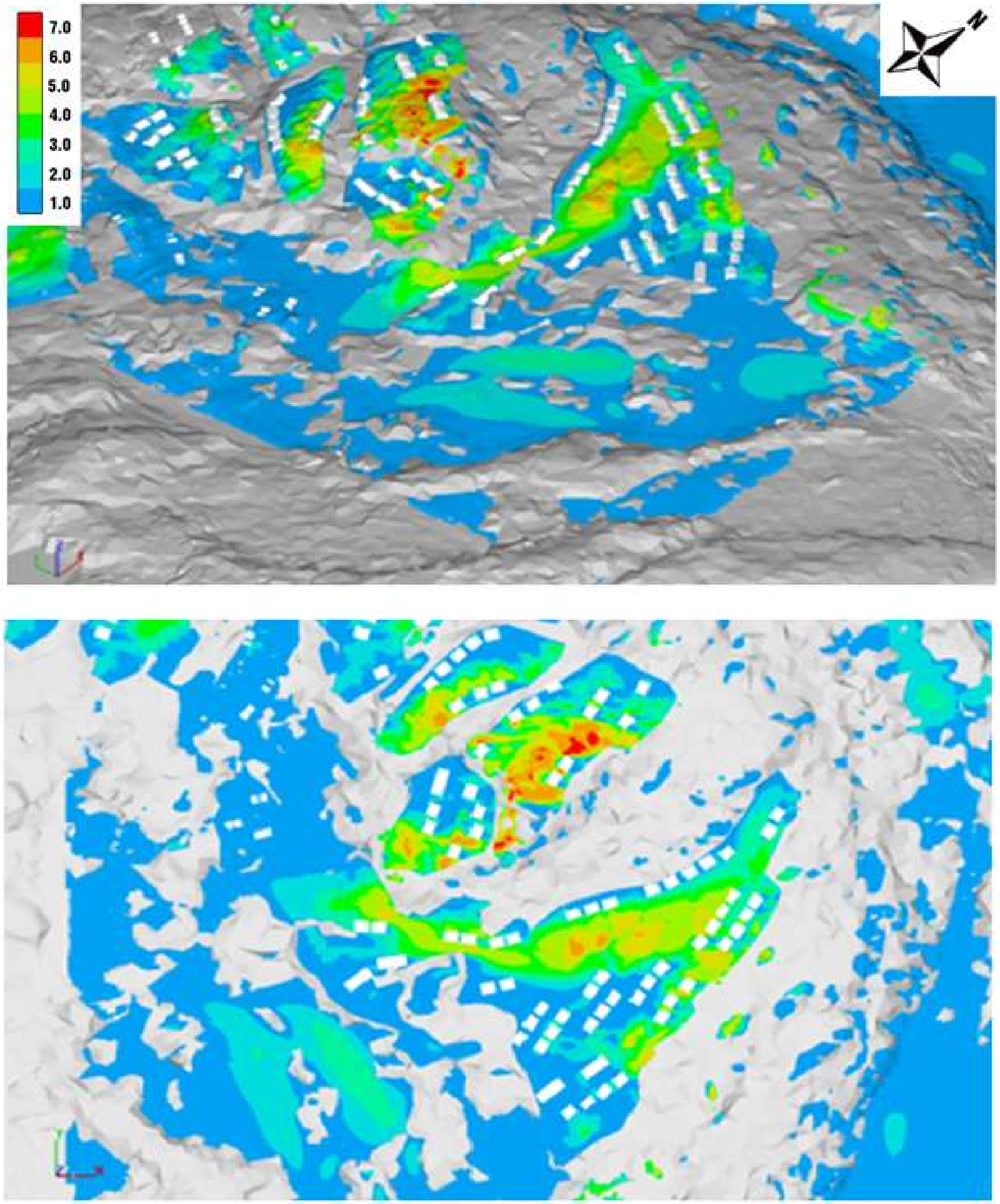

Figure 5. SSW wind direction simulation with buildings and new configuration for area C

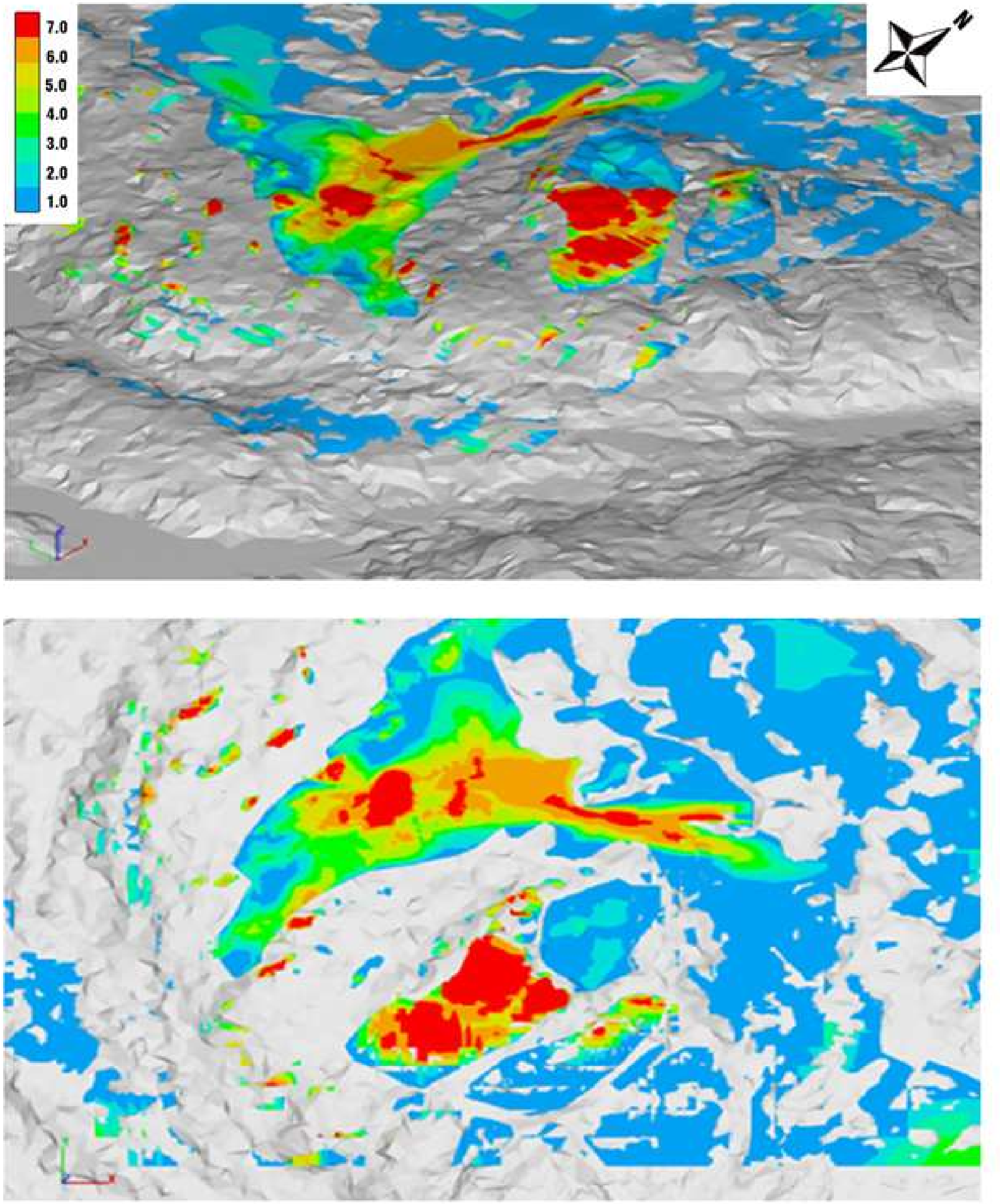

Figure 6. NNE wind direction simulation without buildings and cut down vegetation

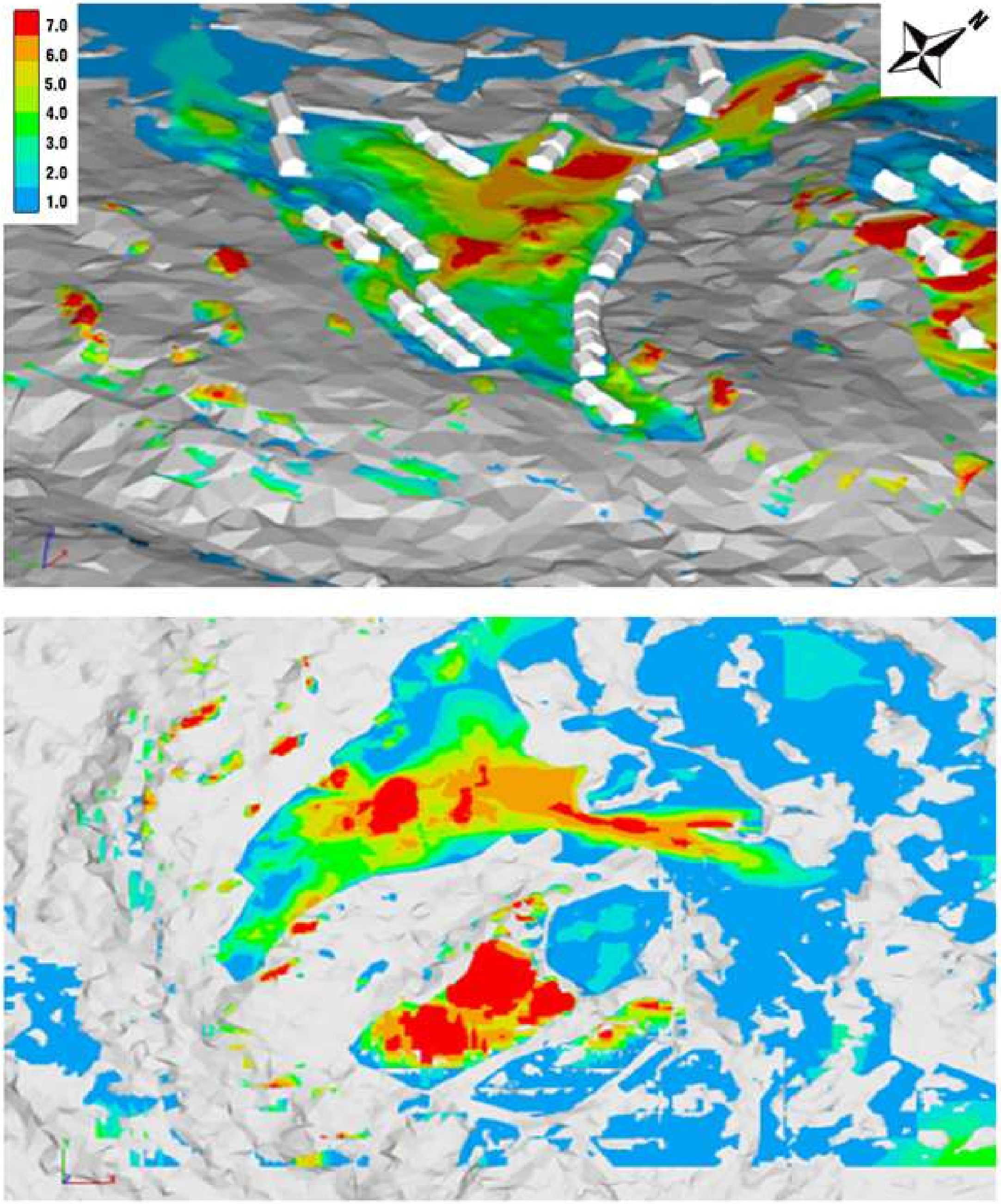

Figure 7. NNE wind direction simulation with buildings for area A

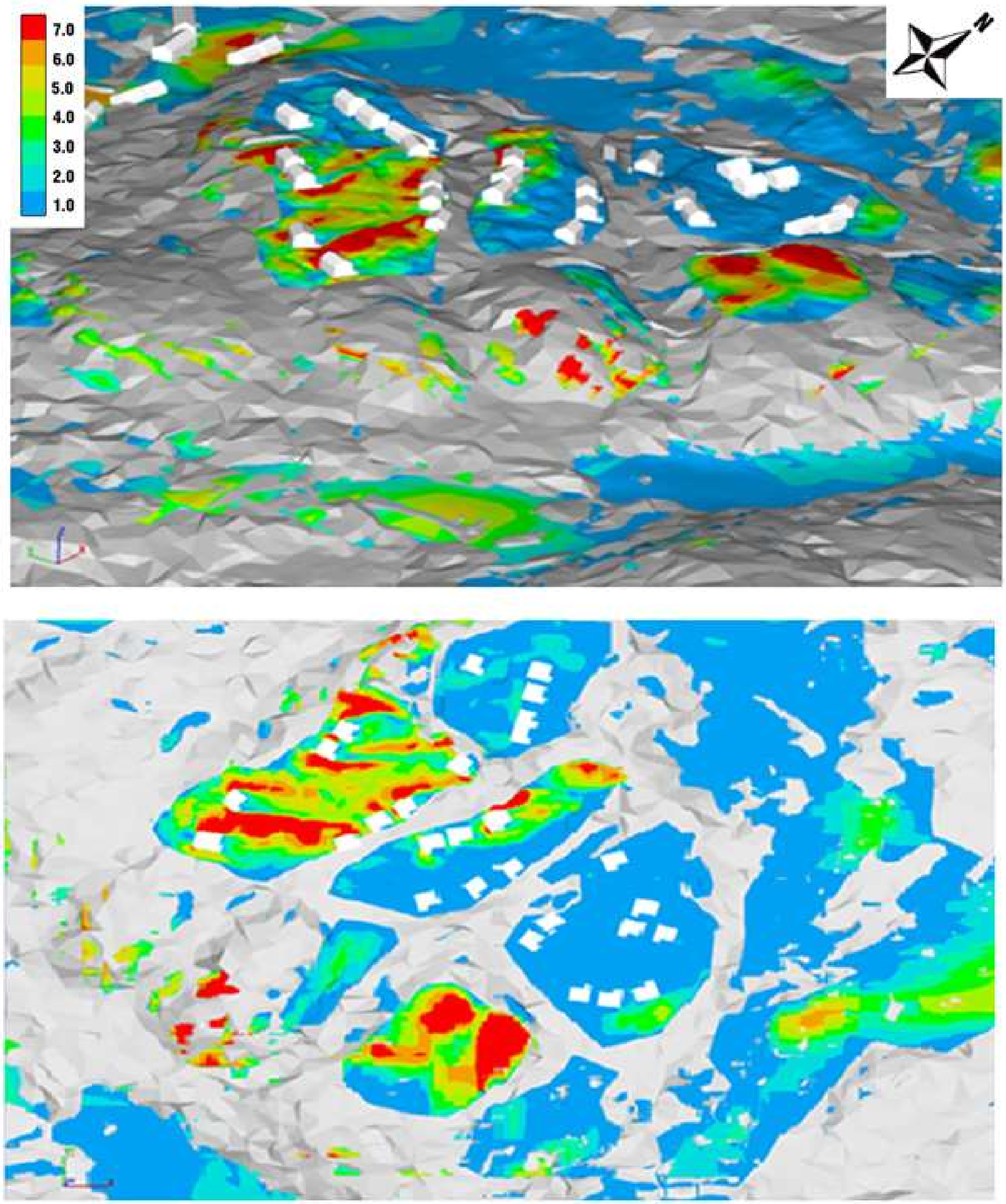

Figure 8. NNE wind direction simulation with buildings for area B

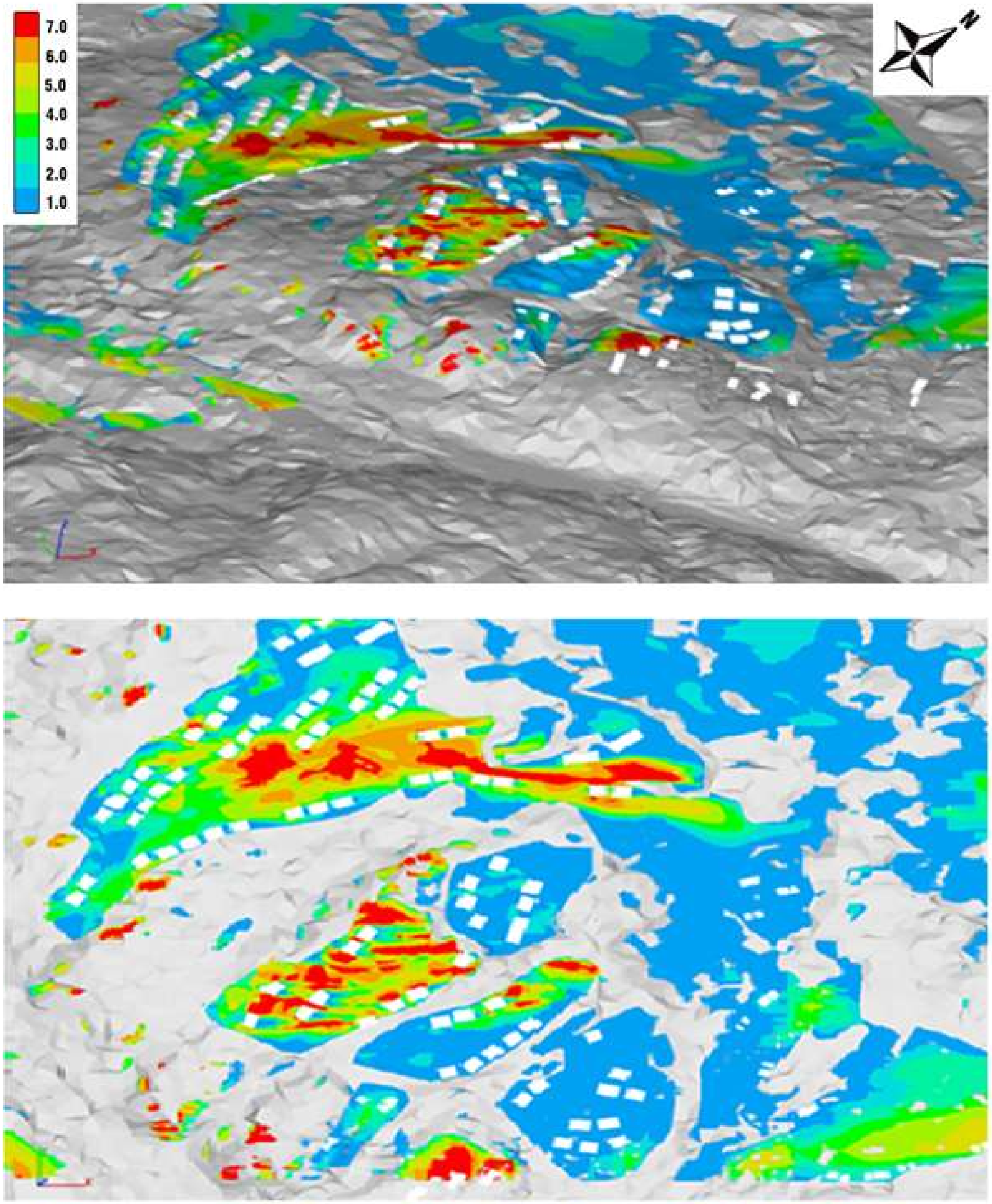

Figure 9. NNE wind direction simulation with buildings for area C

Appendix D - Sketches of buildings

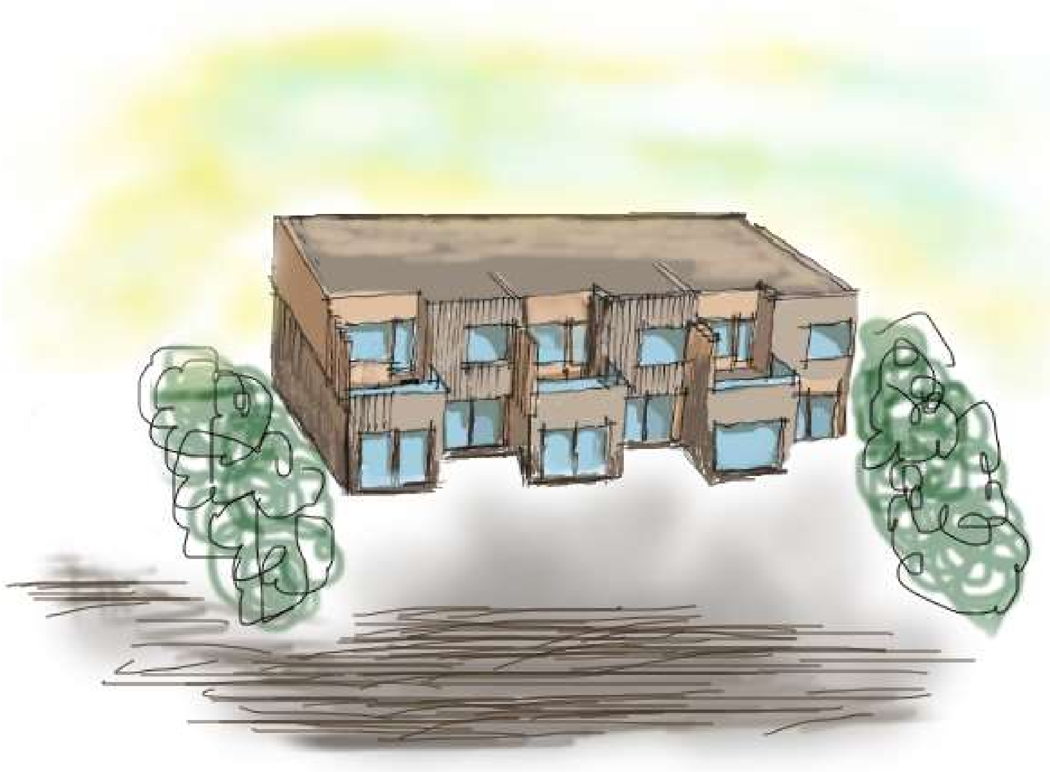

Figure 1. Block type two-storey buildings

Figure 2. Two-storey single houses with garage

Figure 3. Oone-storey single house