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Applying FARSITE and Prometheus on the Västmanland Fire, Sweden (2014): Fire Growth Simulation as a Measure Against Forest Fire Spread

– A Model Suitability Study –

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– *A Model Suitability Study* –

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Preface

This thesis marks the end of three educational and enjoyable years of the bachelor program in Physical Geography and Ecosystem Science. The course is given at the Department of Physical Geography and Ecosystem Science at Lund University, Sweden, and comprises 15 ECTS credits. We would like to thank the following persons for their support and guidance that made this work possible:

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Author Contributions

Since this thesis is written by two authors, it includes author contributions to facilitate individual assessment. The work were divided as follows: Henrik Hagelin is responsible for the conception and design of the thesis, the theoretical background to forest fire mechanisms, the literature review of the Västmanland Fire, acquisition of data, and the main revision of the work. Matthieu Cluzel is responsible for preparing the data and inputs for the models, the modelling, interpretation of model outputs, and map generation. Both are responsible for the theory behind the models, analysis of the results and the discussion.

Abstract

In 2014, the Västmanland County in Sweden suffered from a severe forest fire that grew to a size of roughly 13 000 ha. Recent and prevailing weather conditions made the fire overpower the extinguishing ability of the Swedish emergency services, and it ran out of control to become the largest forest fire in Sweden since the middle of the 20th century. The year after the fire, a need to increase the emergency preparedness for complex events, such as the Västmanland Fire, was issued by the Swedish Civil Contingencies Agency. Simulation of fire spread can help to limit the consequences of wildfires, hence this study aims to find out if either of the fire growth simulation models FARSITE or Prometheus, can simulate forest fires in a Swedish environment. The Västmanland Fire was chosen as reference because of its significance in the Swedish history, and it is used to test model suitability. Attempt 1 managed to simulate only 15 % of the reference fire, whilst more than 80 % was replicated by attempt 2. Prometheus proved to be the better alternative due to its simulation results and its COM-based structure. The limited time frame of this work allowed simulation of only one fire which means that the results found in this study should not be seen as a confirmation of suitability but as a start of a larger project. Future works are recommended to further test Prometheus, and needs to focus on the creation of custom fuel types that corresponds to Swedish vegetation.

Keywords
Fire Behaviour · FARSITE · Forest Fire · Model Suitability · Prometheus · Västmanland Fire

Sammanfattning

År 2014 drabbades Västmanland län i Sverige av en allvarlig skogsbrand som växte till att täcka drygt 13 000 ha. På grund av vädersituationen klarade räddningstjänsten inte av att hantera branden, vilken resulterade i att bli den största branden i Sverige sedan mitten av 1900-talet. Året efter branden rapporterade Myndigheten för Samhällskydd och Beredskap ett behov av ökad beredskap för allvarliga händelser så som branden i Västmanland. Då brandspridningssimulering kan underlätta arbetet med att minska konsekvenserna av skogsbränder, syftar denna studie till att undersöka om någon av brandtillväxtsimuleringsmodellerna FARSITE och Prometheus kan simulera skogsbränder under svenska förhållanden. Branden i Västmanland valdes som referens tack vare dess historiska betydelse i Sverige och den användes för att uvärdera modellernas lämplighet. Det första försöket lyckades endast simulera 15 % av referensbranden mendan 80 % blev simulerat under försök 2. Prometheus visade sig vara det bättre alternativet tack vare ett bättre resultat och dess COM-baserade uppbyggnad. Arbetets smala tidsram tillät dock endast simulering av en brand och därför kan inte resultatet i denna uppsats ses som ett bevis på modellämplighet utan snarare som starten på ett större projekt. Framtida studier rekommenderas att fortsatta utvärderingen av Prometheus och behöver fokusera på att ta fram anpassade bränsletyper som är representativa för svensk vegetation.

Résumé

En 2014, le comté de Västmanland en Suède fût confronté à un sévère incendie de forêt qui a atteint une taille d'environ 13 000 ha. Les conditions météorologiques du moment ont conduit ce feu à surpasser la capacité d'extinction des services d'urgence suédois, le rendant hors de contrôle jusqu'à en devenir le plus grand feu de forêt en Suède depuis le milieu du XX^{e} siècle. Suite à cet incident, l'Agence Suédoise de Prévoyance Civile a adressé qu'il était nécessaire d'accroître l'état de préparation en cas d'urgence. Des simulations de propagation de feux de forêts peuvent aider à en limiter les conséquences, cette étude a donc pour but de voir si l'un des modèles de prédiction FARSITE ou Prometheus est capable de simuler des incendies en Suède. L'incendie de Västmanland a été choisi comme référence pour tester l'adéquation des modèles en raison de son importance historique dans le pays. Un premier essai a réussi à simuler seulement 15 % de l'incendie de référence, tandis que plus de 80 % ont été reproduit par le second essai. Prometheus s'est avéré être la meilleure alternative en raison de ses résultats et sa structure basée sur la Programmation Orientée Objet. Le laps de temps limité de cette étude n'a permis la simulation que d'un seul feu de forêt, ce qui signifie que les résultats trouvés ne doivent pas être considérés comme une finalité mais comme le début d'un travail à long terme. Il est recommandé de tester davantage Prometheus dans de prochains travaux avec en plus la nécessité de créer des carburants spécialisé correspondant à la végétation suédoise.

Nomenclature

Abbreviations

FBP System	Fire Behaviour Prediction System
MODIS	Moderate Resolution Imaging Spectroradiometer
MSB	Swedish Civil Contingencies Agency
NASA FIRMS	NASA Fire Information for Resource Management System
NFFL	National Forest Fire Laboratory
SLU	Swedish University of Agricultural Sciences
SMHI	Swedish Meteorological and Hydrological Institute

Terminology

Fire flanks	The flanks of a growing fire that are roughly parallel to the fire front
Fire front	Foremost fire line of a wildfire with continuous flaming combustion that indicates the main fire growth direction
Fire head	Fastest spreading part of a fire – multiple fire heads may be present
Fire rear	Backside of a fire that expands in the opposite direction than the fire front
Fire spot	A burning region located outside the main fire that is ignited by wind spread burning matter
Firebreak	Barrier that prevents further fire spread in that direction – has either natural or anthropogenic origin
Flame stage development	Describes the life of a fire which corresponds to the development of a flame – shown graphically with intensity as a function of time

Flash point	The lowest temperature required for a substance to release a sufficient amount of vapor through pyrolysis to ignite
Ignition point	Refers to the initial starting location of the fire
Pyrolysis	Thermochemical decomposing of organic matter
The Västmanland Fire	Refers to the large forest fire that raged in the Västmanland County, Sweden, in 2014, and which is used as reference fire in this work
Wildfire	Umbrella term for an uncontrolled non-structure fire in the countryside that threatens to destroy life, property, and natural resources

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Chapter 1

Introduction

In late summer of 2014, almost 10 000 ha of forest were devastated by a forest fire in the Swedish municipality Sala, located in the Västmanland County. A spark from a forest scarifier initiated the fire, and a recent heatwave followed by low relative humidity and strong winds allowed a rapid fire spread with a maximum estimated velocity of 5 km/hour. Swedish rescue services had difficulties countering the fire that grew for about a week, and it became the largest forest fire in Sweden since the middle of the 20th century (MSB 2015). The year after the Västmanland Fire, the Swedish Civil Contingencies Agency issued the need for an increased emergency preparedness and response to major un-plannable events, such as forest fires, in Sweden (MSB 2016).

Wildfire is the main threat to forested areas in Europe, and every year terrestrial ecosystems around the world are stressed by fire hazard (Krivtsov et al. 2009; Coppola 2011; Guha-Sapir et al. 2016). Williams (1977) has said that the re-occurence of wildfires often means a substantial short-term economic loss for forest owners, and it is therefore important to study wildfires to design measures to minimize damage. Fire growth simulation is an effective measure that can help limit the consequences of wildfires because it allows local authorities to correctly relocate fire extinguishing resources.

1.1 Aim with Objectives

This work aims to evaluate whether the models FARSITE and Prometheus are suitable for use in Sweden. In order to evaluate the model output, the Västmanland Fire was chosen as reference due to its great impact in Sweden, and because it ought to be well-documented. Three objectives are used to achieve this aim, and which are shown in the list below:

α Literature will be reviewed to gain an understanding of the theoretical background to forest fire mechanics. Important factors behind wildfire growth will be highlighted.

β Review of the days with fire growth during the Västmanland Fire. This will allow better evaluation of FARSITE and Prometheus.

γ Simulate the Västmanland Fire by running FARSITE and Prometheus on data from the event. Their outputs will be compared to the daily extent of the Västmanland Fire.

1.2 Project Limitations

Due to the short time frame of eight weeks for this project, the following limitations have been applied.

- This study is about forest fires in Sweden and therefore the focus is solely put on wildfires in boreal forest biomes despite the fact that fire mechanics may differ between forests in different climate zones.

- Sweden is located in the Northern Hemisphere and therefore southern slopes are considered warmer than northern slopes. The opposite applies in the Southern Hemisphere but is not accounted for.

- The Västmanland Fire is the only fire that is used as reference when evaluating suitability of the two models. The result is seen as an indicator of whether the models are suitable for wildfire spread simulation in a Swedish environment. A positive result where the output from one of the models matches the reference fire is not a proof of suitability, but an indication that the model could be suitable for use in Sweden. Similarly, a negative result where a model output deviates from the reference fire is not a proof of non-suitability.

- All optional input parameters will not be modelled. For example, barriers caused by rescue services can be identified to some extent from literature, but their exact spatial location is unknown.

Chapter 2

Theoretical Background

This chapter intends to increase understanding of the complexity behind fire growth simulation modelling. Section 2.1 is about the theoretical background of forest fire mechanics, in which fundamentals of basic fire science is explained before moving on to the more complex forest fires. The focus is put on combustion of organic matter since that is the most common source of fire fuel found in forests.

The subsequent sections 2.2 and 2.3, aim to introduce the models FARSITE and Prometheus. Both models simulate fire growth based on the same principle and requires the same type of spatial data, but contain vast structural differences. These sections contain a brief background to each model, and their required inputs are described.

2.1 Forest Fire Mechanics

All known matter can be considered as fire fuel as they burn under the right conditions. For a fire to ignite, a mixture of the three components heat, oxygen and fuel has to be present. The mixture composition depends on fuel type characteristics such as porosity. For example, wood requires less energy to reach its average flash point of 300 ℃ than steel, which has a flash point of 1 400 ℃.

When organic matter is heated, it will eventually start pyrolysing. If the right quantity of oxygen is present, the vapourised gases will ignite when the flash point is reached. The phrase *burning matter* is used in this report instead of *burning vapourised gases* for simplicity and to avoid confusion, but it is important to note that it is the gases released during pyrolysis that fuel a fire and not the solid matter itself.

Fire spread will occur solely if the radiative energy of the burning matter is enough to heat surrounding matter to its flash point. If the intensity is too low to enable fire spread, the fire will go extinct due to insufficient energy supply. Similarly, a fire will go out if oxygen supply is disrupted or when all fuels have been combusted.

The behaviour of a fire is controlled by factors that often depend on environment in which the fire takes place (Chandler et al. 1983; Bengtsson 2001; Hansen 2003). For example, indoor fires are often controlled by limited ventilation and fuel availability (Bengtsson 2001), while forest fires usually have unlimited oxygen supply and vast fuel supply. Forest fires are instead mostly controlled by fuel type, recent and current weather conditions, and topography (Hansen 2003).

2.1.1 Fuel Type

A forest contains a lot of different types of organic matter which can be categorized as either dead or living fire fuel. More finely divided matter, such as grasses, leaves, needles and bushes, catches fire more easily and has a faster flame stage development than more compact matter such as branches and stems. This is because finely divided matter is more porous than compact matter, and has a larger area in relation to its volume where pyrolysis can take place (Bengtsson 2001; Hansen 2003). A faster fire stage development means that the fuel will be combusted at a higher rate, so the types and amount of available fuels can therefore be used as an indicator for how long a fire will go on.

Organic matter in forests is exposed to the environment and therefore usually contains a moisture content of 10 to more than 20 % (Simard 1968; Hansen 2003). A moisture content below 5 % poses a great fire risk. Moisture content is measured as the fraction of kilogram moisture in relation to the total mass of the matter. Matter with high moisture content requires more energy to ignite than dry matter because parts of its moisture content have to evaporate to allow ignition. Dead matter dries quicker than living matter, and finely divided matter loses moisture faster than compact matter (Chandler et al. 1983; Hansen 2003).

Most forest fires rage in coniferous forests because deciduous tree species contain more moisture than coniferous trees. When forest fires affect deciduous forests, it is not unusual that the fire combusts the lower vegetation while leaving the trees untouched (Hansen 2003). Except a lower moisture content due to different characteristics between tree species, coniferous forests are often of low average age due to forestry. Younger trees photosynthesize more than older trees which means a more rapid moisture loss through transpiration, and an increased sensitivity to fire.

The ratio between fire fuel area and fuel volume is often associated with fire load intensity (Bengtsson 2001). The more fuel that is exposed to fire, the more energy can potentially be released and which results in an intensity increase. This affects the distance a fire can spread since a higher energy intensity enables fire spread over longer distances.

According to Hansen (2003), fuel continuity describes the organic matter distribution both horizontally and vertically. It can be used as a measure of how fires can spread in a forest. In a simplified representation of vertical fuel continuity in a forest, roots and decomposed matter are located below the forest floor buried in the soil. The soil is often covered by a mixture of dead branches, needles, leaves and lower grasses. Bushes and longer grasses are found at the next level and possibly low hanging branches from trees. The higher levels are dominated by trees. Fires often start at ground level where the most finely divided organic matter is found, and then spreads vertically through the different levels. Similarly, horizontal fuel continuity describes how horizontal distribution of dead matter and vegetation allows horizontal expansion of the fire front.

2.1.2 Weather

Modelling weather is complex because of many and constantly changing variables which vary in both space and time (Chandler et al. 1983; Hansen 2003). Risk of fire in an area is therefore controlled by recent and current weather conditions. Both local variations and variations on a larger scale have to be considered.

Solar radiation heats the atmosphere, which on a local level causes a lowering of the moisture content in organic matter. Higher air temperatures also means that less energy is needed for the flash point to be reached. The intensity of solar radiation varies with time of day and seasonality, but can also be reduced by the shielding effect caused by clouds (Hansen 2003). Another source of energy that affects air temperature is terrestrial radiation. Compared to solar radiation, it contains less energy and is emitted from the Earth itself. Because of that, it is more even throughout the year and it cannot be prevented by clouds.

It is solar radiation which mainly causes variations in air temperature on a larger scale, and this results in atmospheric circulation. The larger the temperature variation is between two areas, the stronger the wind will be between them. For already raging fires, strong winds mean a rapid increase in fire load intensity because of the added oxygen supply. Fire growth can be enhanced even more if small pieces of burning matter is uplifted, and transported by the winds to form fire spots. That way the fire can spread faster into areas where the emitted radiation cannot reach. Normally, fires spread in the same direction as the wind, and therefore wind direction is often used as a measure when determining rate of fire growth (Chandler et al. 1983; Hansen 2003).

For local fire risk level, winds mean that air temperatures can fluctuate depending on the temperature of the approaching winds. Winds also often change the relative humidity of air, which in turn affects the moisture content of organic matter. The moisture content of dead organic matter tends to be the same as the relative humidity in the surrounding air, meaning that a lowering of relative humidity increases the risk of fire. Similarly, the risk of fire is reduced with increasing relative humidity. Hansen (2003) says that changes in relative humidity also affect the moisture content of living organic matter, but at a slower rate than that of dead matter. For an ongoing fire, increasing air moisture content cause a cooling effect which reduces fire growth. This is because heat from the fire is absorbed by the liquid water in the air which at 100℃ turns into vapor. The phase change is what has the greatest cooling effect on the fire.

Chandler et al. (1983) and Hansen (2003) state that the rate of fire growth can be enhanced if the atmosphere is unstable. During unstable conditions, the atmosphere is more turbulent and there is more uplifting of air than during stable conditions. This means that the smoke from the fire is pulled upwards while fresh air is sucked into the fire, and which results in an increased fire load intensity. Atmospheric instability can also lead to the formation of thunderstorm clouds. As a consequence of this, the risk of fire increases because cloud-to-ground lightning is a common source to wildfires.

Formation of clouds can also lead to precipitation, which has an influencing effect on moisture content of organic matter. The influence of light rainfall for an extended period is greater than that of a short downpour (Simard 1968; Hansen 2003), and it is therefore important to consider recent weather conditions when determining fire risk level. Rainfall during an ongoing wildfire has an extinguishing effect and will reduce fire growth. Another way in which rainfall reduces risk of fire and limits fire growth, is by increasing the relative humidity.

2.1.3 Terrain

Both aspect and inclination of slopes affect fire risk level and rate of fire growth (Chandler et al. 1983; Hansen 2003). In the Northern Hemisphere, risk of fire is greatest on southerly facing slopes because of in general warmer air temperatures that result in drier fire fuel and more atmospheric instability. Hansen (2003) says that the rate of upwards fire spread can be assumed to double with every 20th percentile increase in slope, and it is therefore important to know where on slopes fires are located when determining fire growth.

Some landforms can increase rate of fire spread more than others. In valleys it is common that fires are spread by the wind to the opposite valley side, and in ravines a phenomenon called *the* *chimney effect* may arise (Hansen 2003). Because of the steep slopes of ravines, air is flowing vertically upward resulting in a suction force that accelerates fire spread. The phenomenon is named after the effect that can occur in chimneys (Bengtsson 2001).

Water courses and bare lands are natural elements that function as barriers to fire spread and they have to be taken into account when modelling fire spread. Even parcels of deciduous forest can act as barriers because of their resistance to fire. Roads, power line corridors, and plowed agricultural fields are examples of anthropogenic barriers.

2.1.4 Additional Fire Behaviour Affecting Factors

The height above sea level affects fire behaviour to some extent. Vegetation is often more dense at lower altitudes which means a greater supply of fuel for fires. The relative humidity of air is also often lower closer to the sea level because of higher air temperatures. This increases the risk of fire because moisture content of organic matter is influenced by the relative humidity (Hansen 2003).

A forest fire, such as the Västmanland Fire that covers a large area, can influence the weather within the same region (Hansen 2003). The vast amount of emitted energy increases the air temperature, which results in atmospheric instability. This means that forest fires can create a self beneficial situation where smoke is pulled upwards while fresh air is sucked into the fire.

2.2 FARSITE

FARSITE is the abbreviation of the *Fire ARea SImulaTor* that has been under development since it was firstly introduced in the USA in the early ’90s (Finney 1994). The simulator is designed to simulate fire growth in two dimensions (Finney 1994; Grant Pearce 2009), and it benefits from several incorporated fire behaviour models (Finney 2004). A model by Van Wagner (1977) allows canopy fires to represent ignition points, while models by Rothermel (1972, 1991) enable fire spread simulations in all vertical continuity levels. Additionally, FARSITE can approximate moisture content of organic matter, and predict fire spotting as a result of the integration of models by Albini (1979) and Nelson Jr (2000) (McHugh and Finney 2016).

When FARSITE simulates fire growth, it uses equations by Richards (1990) that are based on the Huygens Principle for light wave propagation. This principle states that every point on a wave front represents the source of a new wavelet that expands outwards, and that the tangent of all these newly formed wavelets represents the new front (Finney 2004; Tymstra et al. 2010). Theoretically, this means that the fire front broadens symmetrically with increasing distance from the ignition point, but in reality this rarely happens because of intensity differences between flames.

Sections 2.2.1–2.2.5 describe the necessary input data that are required for FARSITE to operate. These data are related to the physical geography of a region, and can be represented by heterogeneous conditions over long time periods.Optional inputs that enhance the fire growth simulation are addressed in section 2.2.6. When a simulation has completed, the resulting fire growth maps can be exported as either ASCII grids or Esri shapefiles, which allow comprehensive analysis of the results (Grant Pearce 2009; McHugh and Finney 2016).

2.2.1 Landscape File (.LCP)

The .LCP file is a binary file with spatial data themes that represents regional properties for terrain and fire fuel distribution, as well as instructions for combustion of available vegetation. Themes for elevation, slope, aspect, canopy cover, and fuel model index, are required, while others for stand height, height to live crown base, crown bulk density, duff loading, and course woody profiles, are optional. The needed themes are detailed in the list below, whilst description of the optional themes are found in the online documentation (McHugh and Finney 2016).

- **Elevation**: Holds values that represent elevation above sea level. Permits adiabatic adjustments of temperature and humidity, and allows conversion of fire growth between horizontal and inclined surfaces. Values can be stored as either SI or imperial units.

- **Slope**: Used for the computation of fire spread along slopes, and considers the affect of solar radiation. Should preferably hold values as integers but decimal values are supported. Units can be in degrees or percentages.

- **Aspect**: Used by FARSITE to estimate incoming solar radiation. GIS software dependent values. Has to be in degrees rotated clockwise from north (azimuth values) if exported from ArcInfo. Supported as either integer or decimal values.

- **Canopy cover**: Allows computation of wind reduction and ground shadowing caused by higher trees. Represented by the direct shading from the above canopy cover, and is different from the ecological condition crown closure which refers to the relative tree crown density. Categorized as either integer units or percentages in the ranges 1 (1-20 %), 2 (21-50 %), 3 (51-80 %), or 4 (81-100 %). A value of 0 or 99 represents zero canopy cover.

- **Fuel model index**: An ASCII file in which each integer value represents a fuel type. Each value instructs FARSITE to call the corresponding algorithm for combustion of that specific fuel. 1-13 represents the standard NFFL fuel models (documented by Rothermel (1972), Albini (1976), and Anderson (1982)), and 0, 98 and 99 represent non fuels. Custom fuel models can be used, but these require the optional Custom Fuel Models (.FMD) input (McHugh and Finney 2016).

2.2.2 Initial Fuel Moisture File (.FMS)

Tab delimited text file in ASCII format with the column headers FuelMod, 1Hour, 10Hour, 100Hour, LiveH and LiveW. The file contains integer information about initial fuel moisture that evolves over time relative to prevailing weather and terrain. It must contain relative humidity and precipitation values for the day prior to ignition, and is used by FARSITE when calculating initial site specific fuel moisture at every new simulation cycle.

FuelMod corresponds to the values in the fuel model index theme assigned to the .LCP file (section 2.2.1). The 1Hour, 10Hour, and 100Hour columns hold values that represent the fraction of moisture in each vegetation type after 1, 10, and 100 h respectively. Those three categories may exceed 100 %. Living fuel is constituted by LiveH (Live Herbaceous) and LiveW (Live Woody), and can obtain a maximum value of 100 %. LiveH and LiveW are constant throughout the simulation unless they are modified manually. Instructions of how to set up initial fuel moisture for custom fuel algorithms are available in the online documentation (McHugh and Finney 2016).

2.2.3 Adjustment File (.ADJ)

Rate of fire spread during a FARSITE simulation, can be fine-tuned to match local variations in order to reduce the over prediction due to coarse spatial and temporal resolutions. This is made by the use of adjustment factors that are allowed to be any floating value above zero. Adjustment factors are fuel model specific, meaning that an adjustment factor has to be applied to each fuel model in the fuel model index theme (section 2.2.1). Multiple .ADJ files can be implemented in a simulation, and every file has to be in space delimited ASCII format with the column heads FuelMod, and AdjustmentFactor. A simulation will proceed without any adjustments if all factors are set to 1.

2.2.4 Weather File (.WTR)

A .WTR file supports both metric and imperial units, and the values must be integers. Each file holds temperature, precipitation and relative humidity data from one weather station, and must contain the column headers Month, Day, Precip, Hour1, Hour2, Temp1, Temp2, Humid1, Humid2, and Elevation. Daily minimum and maximum temperature and relative humidity values are stored in the fields Temp1 and Temp2, and Humid1 and Humid2 respectively, while Hour1 and Hour2 corresponds to the hours with the lowest and highest temperatures during the day. FARSITE uses this information to interpolate weather across the studied region, and extrapolates weather on different elevations. Up to five .WTR files are allowed meaning that weather variations can be modelled to some extent.

2.2.5 Wind File (.WND)

Information about wind velocity and direction is stored in the .WND file, which is a tab delimited ASCII file with the column headers Month, Day, Hour, Speed, Direction, and CloudCover. All values have to be integers, and both metric and imperial units are supported. Hour is stored as nearest minute within a rage of 0-2 400. The field Speed holds the wind velocity in mph or kph, while the Direction field stores the wind direction as a clockwise rotated degree (0-360) starting at north. CloudCover is stored within the rage of 0-100 %. Every .WND file can contain information from one weather station, but since up to five .WND files can be included in a simulation, data from multiple stations can be used. FARSITE treats winds as variable in time but constant in space, and the model can not simulate winds in complex terrain such as in canyons.

2.2.6 Additional Inputs

FARSITE can benefit from the use of eight optional inputs including the integration of barriers caused by aerial, and ground based fire fighting. Daily burning periods can be specified to prevent simulation during occasions of low burning activity, and the fire intensity of a source can be adjusted manually to fix incorrect spread rates. The web-based user guide provides further information about how to set up and integrate these inputs in FARSITE (McHugh and Finney 2016).

2.3 Prometheus

In 1999, development of the Canadian Wildland Fire Growth Simulation Model, named after the Greek God Prometheus, began. Three years later, the first software version was released. Prometheus is still evolving, and it is based on a combination of equations by Richards (1990, 1993, 1995, 1999), that are further developments of the Huygens Principle for light wave propagation (concisely described in section 2.2), and the *Canadian Forest Fire Behaviour Prediction* (FBP) System. The FBP System can relate wind, fuel moisture, and 16 vegetation types to fire behaviour characteristics during a single burning period, and from a single ignition point represented by either a point or a line. Uniformal and continuous fuels, simple and homogeneous topography, and constant and unidirectional wind are assumed. This means that Prometheus would be unsuitable for wildfire simulation if it were solely based on the FBP System, but the combination with the Richards (1999) equation allows fire growth simulation on both flat surfaces and in complex terrain (Tymstra et al. 2010). The resulting maps can be shown visually in Prometheus, or exported as shapefiles to be viewed externally.

Certain data files have to be prepared before being imported into Prometheus. These files contain information about ignition, regional properties such as terrain and weather, and information about fire behaviour in different fuel types. Section 2.3.1 provides information about these data files, while section 2.3.2 aims to give a general overview of how Prometheus operates.

2.3.1 Input Data

Data sets with information about landscape related features within a region must be in Esri grid format. This is because Prometheus simulates fire growth in a grid-based environment. Three data sets and one ignition feature are required as inputs when simulating fire growth in complex terrain, and they have to cover the same extent and have the same projection. Optional inputs such as water courses and roads that can be used as barriers, are allowed in any projection (Tymstra et al. 2010). The needed inputs are briefly described in the list below:

- **Fire initiation (.shp or .gen)**: Contains information about geographical coordinates for an ignition point, which can be of either point, line, or polygon shape. Multiple Fire initiation data sets can be imported meaning that Prometheus supports multiple ignition points. Geographical projection is assigned when preparing the model.

- **Topography (.asc)**: Elevation is stored as height above sea level in meters, slope in percentages, and aspect in compass degrees. These three variables are necessary as inputs if the simulation will take place in a three dimensional environment, whereof aspect and slope can be calculated by Prometheus from the elevation. The elevation parameter also allows Prometheus to compute the *Foilar Mosture Content* (FMC) from the FBP System, which represents the moisture content of canopy fuels. FMC can be assigned manually.

- **Fuel Type Grid (.asc)**: This data set contains information about available fuel types in a region, and is used by Prometheus to define the grain and spatial extent of the results. Since Prometheus is based on the 16 fuel types in the FBP System, an integer value has to be assigned to each fuel type in the grid that represents a link to a corresponding fuel type in the FBP System. This link is required to provide Prometheus with instructions of how to combust that specific fuel.

- **Weather (.asc)**: Weather is a driving factor when simulating fire growth. Prometheus can handle varying weather data because of its *Fire Weather Index* (FWI) System that handles data such as temperature (℃), relative humidity (%), precipitation (mm), and wind velocity (kph) and direction (compass degrees). The FWI System is built up by the following indexes that are used by the Prometheus COMs (section 2.3.2); *Fine Fuel Moisture Code* (FFMC), *Duff Moisture Code* (DMC), *Drought Code* (DC), *Initial Spread Index* (ISI), *Buildup Index* (BUI), and *Fire Weather Index* (FWI). A more complete explanation of the different indexes are found in the recommended documentation by Tymstra et al. (2010). A minimum of one nearby weather station is required for the FWI System to operate, and multiple stations are supported. Prometheus issues a warning if the nearest station is located farther than 100 km away.

2.3.2 Prometheus COMs

Prometheus is based on the technology *Component Object Model* (COM), and is built up by modules. This structure allows exportation of modules for use in other applications, and that new modules can be imported rather easily to increase functionality. Recent versions of Prometheus implement five different modules in the default configuration (FireGrowthModel.ca 2014). Those are briefly described in the list below:

- **FireEngine**: Incorporates COMs that drive the simulation based on fire growth affecting parameters from the input data (section 2.3.1), such as ignition points and statistical information about fuel types (extracted from the FuelCom module).

- **FuelCom**: Holds information about the fuel type standards found in the FPB System. Every fuel type has two interfaces that (**i**) can modify and examine different fuel type specific aspects, and (**ii**) allow other modules to extract statistical information about the fuel type. The interfaces are separated to avoid conflicts when implementing custom fuel types.

- **FWICom**: Collection of methods that provides relative measures about fire behaviour potential based on fuel moisture for every fuel type.

- **GridCom**: Contains code that handles all statistical spatial data, and manages the FuelCom module defined COMs. It also includes a COM that can store and edit .shp and .gen vector files.

- **WeatherCom**: The WeatherCom module relies on functionality provided by the FWICom and GridCom modules. It concerns data that supports forest fire simulation, and incorporates different COMs that for example store information from a weather station, and performs spatial interpolation of weather data. The stored information are available when needed during an ongoing fire growth simulation.

Chapter 3

Methodology

The purpose of this chapter is to describe the steps in which the simulations in this study were performed. Section 3.1 provides an overview of the data sets needed by FARSITE and Prometheus, while section 3.2 illustrates how these data were prepared to match the model specific requirements presented in section 2.2 and 2.3. These sections only cover the methodology involving fire growth simulation. Concerning the literature study, the focus was put on reviewing reliable collections consisting of operation and observation reports, and analyzes from the Västmanland Fire, that were issued by Swedish authorities.

All GIS related operations were carried out in Esri ArcMap 10.2, and PaintNet was used for graphical processing. FARSITE 4.1.055 (released 27 May 2008), and Prometheus 6.1.0 (released 1 January 2015) were the models used to perform the simulations.

3.1 Description of Data

A description of the data sets used in this study is found in section 3.1.1–3.1.6. The metadata are structured in lists rather than in blocks of texts to make it easier to grasp. Information such as type, spatial resolution, and a brief descriptive background are provided for most data sets.

3.1.1 Digital Elevation Model (DEM)

Type: GeoTIFF (.tif).
Date of creation: 2009.
Spatial resolution: 2 m.
Reference System: SWEREF 99.
Description: Laser scanned DEM that represents the regional terrain.
Source: Land Survey of Sweden (2009).

3.1.2 Outer Boundary of the Västmanland Fire

Type: Polygon feature (.shp).
Date of creation: 2014.
Reference System: SWEREF 99.
Description: Illustrates the outer boundary of the Västmanland Fire. Used as ground reference.
Source: SLU (2014).

3.1.3 Vegetation Inventory Data

Type: Polygon feature (.shp).
Date of creation: 2010.
Reference System: SWEREF 99.
Description: Vector layer that shows regional vegetation distribution. Reclassified to match the corresponding fuel models for each model. A complete list of all vegetation types with corresponding fuel models is displayed in Table A.1.
Source: Land Survey of Sweden and SLU (2012).

3.1.4 Weather Data

Type: ASCII table (.asc).
Date of creation: 2014.
Resolution: Temp., relative humidity, and wind velocity and dir. every 3rd h. Precip. every 12th h.
Reference System: SWEREF 99.
Geographical coordinate: Lat 59.9098, Long 16.6875.
Description: Historical meteorological raw data containing temperature and relative humidity values at a height of 1.5 m, and values for wind velocity and direction at a height of 2.0 m. Precipitation also available.
Source: SMHI (2014).

3.1.5 MODIS Active Fire Data

Type: Point feature (.shp).
Date of creation: 2014.
Spatial resolution: 1 km.
Reference System: WGS 84.
Description: Remotely sensed satellite data which represents detected wildfires. Each point represents a fire within 1 km. Provides a minimum of one image per 24 h. Used when comparing daily fire growth.
Source: NASA FIRMS (2014).

3.1.6 MSB Reported Weather Data

Date of creation: 2014.
Description: Table 3.1 shows interpreted wind data from MSB (2015).
Source: MSB (2015).

Table 3.1: Interpreted values from MSB (2015) that were used as input during the second simulation by Prometheus.

		Jul 31st	Aug 1st	Aug 2nd	Aug 3rd	Aug 4th	Aug 5th
W. Velocity	**(km/h)**	40	43	22	43	43	18
W. Direction	**(°)**	225	225	90	113	135	135

3.2 Modelling Approach

Before inputting any data into the models, they had to be homogenized to match the same extent, resolution and projection. The frame used when clipping the data was created by fitting a rectangular polygon around the extent of the MODIS Active Fire Data (NASA FIRMS 2014), and to which a 5 km buffer was applied. A distance of 5 km was chosen to dedicate more space for the simulations in case the modelled fire growth would expand outside the final boundaries of the Västmanland Fire. SWEREF 99 was chosen as projection, and all raster data were resampled to a 10 m resolution. This resolution was selected because it would reduce both the physical size of the project and the time required for the simulation processes, without significantly altering the quality of the results. A shapefile with the coordinates of the ignition point (WGS 84: Lat 59.840879, Long 16.204462) was also created.

The theory behind the models shows that they require similar base data but different inputs due to structural differences (section 2.2 and 2.3). Information of how to prepare these inputs, and description of how the models where set up prior to start the simulations are found in section 3.2.1 and 3.2.2. Section 3.2.3 concerns an additional simulation that was performed with Prometheus.

3.2.1 FARSITE Specific Preparation

As seen in section 2.2.1, the .LCP file requires information about regional elevation, slope, aspect, canopy cover, and vegetation distribution. Slope and aspects rasters were generated from the DEM in Esri ArcMap 10.2. The canopy cover parameter was set to 100 % considering the season of when the Västmanland Fire took place, and the vegetation inventory data set was reclassified to match the standard NFFL fuel models. Table 3.2 shows this reclassification.

All fuel categories in the .ADJ file were assigned the value 1.00 to prevent adjustment of the simulation. The initial moisture content of fuels was set to 10 % for all fuel types presented in Table 3.2. This decision was considering the minimum relative humidity of July 31st, and a function for fuel moisture content by Simard (1968). A step increase of 10 % for the 10Hour and 100Hour fields was arbitrary chosen, and LiveH and LiveW were assumed to be 100 %.

The .WTR and .WND files were filled with data from SMHI (2014) in accordance with what is described in the sections 2.2.4 and 2.2.5. These data were in metric units. Prior to simulation start, some ASCII files had to be adjusted because the fields xllcorner and yllcorner contained

Table 3.2: Reclassification of regional vegetation to match the corresponding standard NFFL fuel models (Rothermel 1972; Albini 1976; Anderson 1982). Required by FARSITE.

Original Vegetation Type	Raster Value	Model Vegetation Type
Cultivated Areas, Grasslands	1	Short Grass
Bushlands	5	Brush
Bushes Under Trees	6	Dormant Brush, Hardwood Slash
Coniferous Forest	8	Closed Timber Litter
Deciduous	9	Hardwood Litter
Open Water	98	Water
Wetlands	99	Non-Fuel

floating values instead of integers which is not supported by FARSITE. The adjustment induced a minor translation of a few centimeters to those rasters, but it was assumed to have no noticeable effect on the simulation results.

Finally, the simulation was set to run with a 1 h time step, and to store a visualization every 24 h. Perimeter and distance resolution was set to 50 m and all fire behaviour options were turned off in order to reduce the simulation time. The simulation was run between the beginning of July 31st and the end of August 5th.

3.2.2 Prometheus Specific Preparation

The DEM was used as topographic input, and FMC was set to 120 % in accordance to Alexander (2010). Table 3.3 shows the values used when reclassifying regional vegetation to match the FBP System. Concerning the weather input, the *Add Daily* option was chosen before importing daily data of temperature, precipitation, and wind speed and direction from SMHI (2014). Data for every third hour were available but the daily option meant better wind direction values. Values of the lowest daily relative humidity were used due to its great influence of fire growth (see section 2.1.2 and 4.2).

The FFMC, DMC and DC values were set to 90, 55 and 453 respectively in accordance to Malmeström and Millbourn (2015). In order to reduce the simulation time, the distance and perimeter resolutions were set to 5 grid cells which represented 50 m, and all fire behaviour options were unchecked. Prometheus was instructed to display and export the results on a daily bases, and the option to interpolate weather was chosen for a more realistic simulation.

3.2.3 A Different Approach

An additional simulation was performed by Prometheus with the same settings as described in section 3.2.2, except that the wind velocity and direction values were replaced with those interpreted from MSB (2015), and which are shown in Table 3.1. A second simulation could not be performed by FARSITE because the model lacks a weather interpolation feature. The reasoning behind this second simulation is found in section 6.1.1.

Table 3.3: Reclassification of regional vegetation to match the corresponding fuel types in the FBP System (as described in Taylor et al. (1997)). Required by Prometheus.

Original Vegetation Type	Raster Value	Model Vegetation Type
Pine Forests	3	Mature Jack / Lodgepole Pine
Conifers	6	Conifer Plantation
Cultivated Area, Grasslands	32	Standing Grass
Deciduous	50	Boreal Mixedwood - Green
Habitations	101	Non-Fuel
Open Water	102	Water
Wetlands	105	Vegetated Non-Fuel

Chapter 4

The Västmanland Fire

Most of the forest within the burned region lacked roads suitable for fire trucks. The low accessibility and a rapid fire growth due to fire favorable weather conditions, made the Västmanland Fire the largest forest fire in Sweden since the middle of the 20th Century (MSB 2015). This chapter intends to develop an understanding to why the fire became so extensive. The physical geography of the fire affected region is described in the first section (4.1) to give an understanding of preconditions for ignition and fire growth. The subsequent section (4.2) focuses on the days when the fire was growing, and presents a brief summery of the regional impact. Apart from occasions when the Swedish rescue services formed barriers to fire spread, the focal point is put merely on natural contributing factors.

4.1 Regional Preconditions for Fire Growth

As seen in section 2.1, fire growth is largely affected by the physical geography of a region. Terrain properties indicate in what rate a fire can spread in different directions. Type and amount of dead and living organic matter show the fire fuel level, and recent weather controls the likeliness of ignition. Only barriers in the western, eastern and northern parts of the affected region are considered due to the northward fire spread as a result of southerly winds. Weather condition during the fire is described in section 4.2.

4.1.1 Terrain

The 13 000 ha area is mostly flat with an altitude of 100-120 m.a.s.l., except from the northernmost part where Stora Hoberget mountain reaches 178 m.a.s.l. (Land Survey of Sweden 2009; MSB 2015). Kolbäcksån river valley and the lakes Virsbosjön and Åmängen limit westerly fire spread. Svartån river valley and the lakes Fläckesjön and Hördesjön constitutes barriers to the east, and the lake Snyten is located in the north.

4.1.2 Recent Weather

One fourth of the normal precipitation and prolonged periods of higher than normal temperatures made the summer of 2014 very dry. Less than 20 mm of rain fell during the month prior to the fire and the fire affected region experienced two heatwaves. A heatwave is in Sweden defined by SMHI (2011) as a minimum of five following days with a maximum temperature exceeding 25℃. Between July 5th and 10th, the temperature was just bellow 30℃. During the second half of the month, the temperature increased and the warmest days were found between the 20th and the 31st. The relative humidity was around 50-60 % daytime most days in July, and it dropped to 30-40 % the days before the ignition (SMHI 2014; MSB 2015).

4.1.3 Fuel Supply

Most of the forest floor was assumed to be covered by finely divided matter such as blueberry and lingonberry bushes. In the eastern and western directions, the forest was framed by agricultural fields located in the valleys. Because of the recent weather situation, the moisture content of the organic matter was low (MSB 2015). This meant that the area contained a vast supply of easily ignitable organic matter.

Forest distribution in the area before the fire is shown in Table 4.1. Coniferous forest (86 %) was dominating the region and pine (65 %) was the most common specie. The more fire resistant deciduous forest (see section 2.1.1) covered only 4 % of the area. In terms of content organic matter, the coniferous forest provided about 1 200 000 m^3 potential fire fuel which represented 93 % of the total available amount.

Table 4.1: Distribution of forests before the Västmanland Fire. The region was dominated by coniferous forest that covered about 86 % of the area. Pine represented 65 % of the coniferous species and 24 % was mixed. Only 4 % of the area was covered by deciduous forest. Table modified from Nilsson et al. (2014).

Forest type	**Area (ha)**	**Volume (m^3)**
Pine forest	5 364	673 676
Spruce forest	945	220 899
Mixed coniferous forest	1 962	276 538
Deciduous forest	396	31 185
Mixed forest	729	59 178
Bare land or recently planted forest	180	0
Total	9 576	1 261 476

4.2 Fire Growth in Daily Chronological Order

On July 31st, 2014, SMHI raised the fire risk level in the area to extreme as a result of the recent weather situation. In the afternoon during the same day, the Västmanland Fire was ignited by a sparkle from a forest scarifier located at SWEREF 99: N 6634304, E 567502. When the fire was reported to the Swedish emergency services operator at 13:29 local time, it was estimated to cover an area of 600 m^2 (MSB 2015).

The sections 4.2.1–4.2.6 describe prevailing weather conditions, and observed and estimated fire spread during the days when the Västmanland Fire was growing. Identified barriers to fire spread are emphasized. Lastly, a brief summary of regional impacts caused by the Västmanland Fire is found in section 4.2.7. Figure 4.1 provides a regional overview to ease the reading.

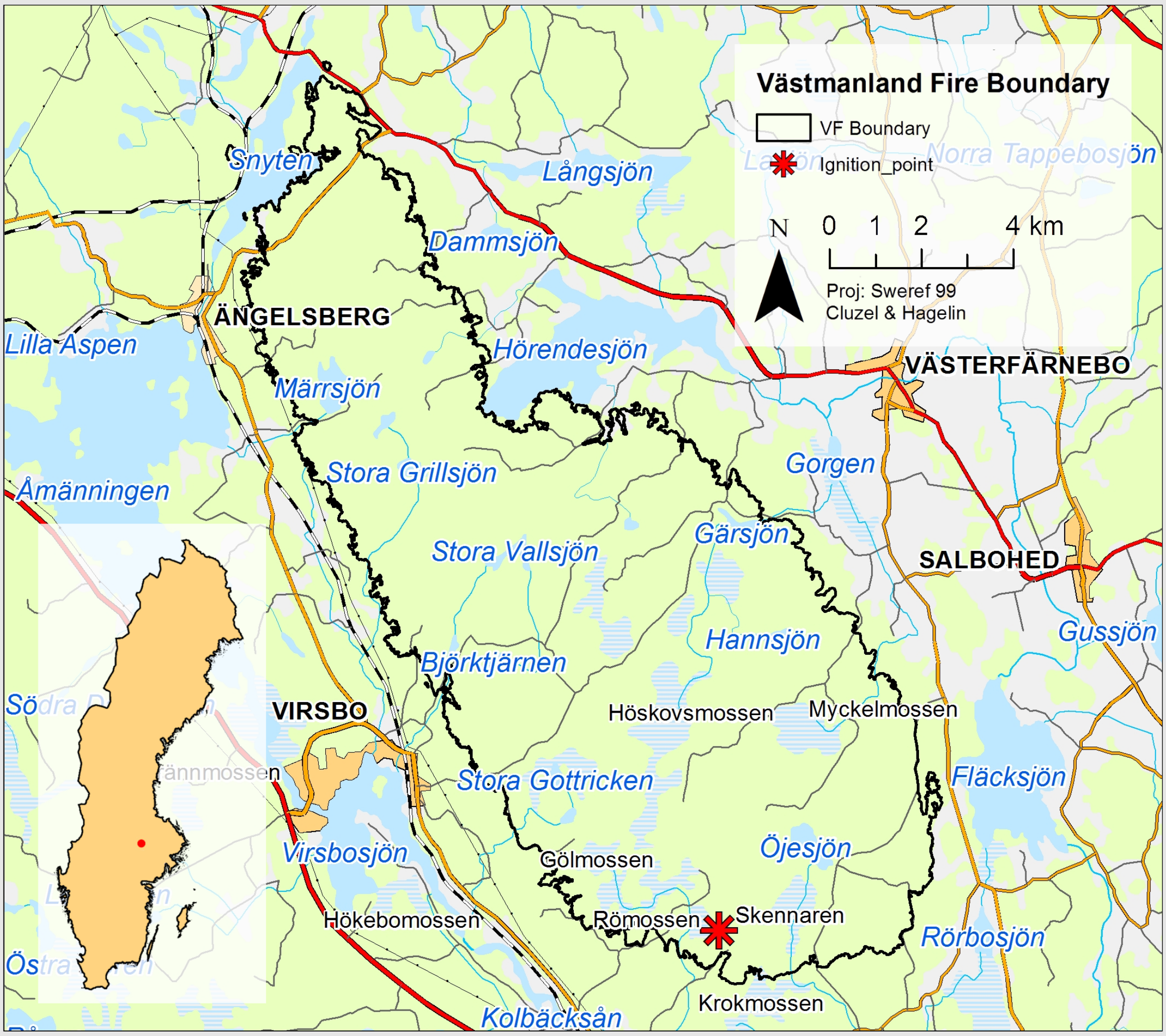

Figure 4.1: Visual overview of the fire affected region. Background map obtained from Land Survey of Sweden (2015).

4.2.1 July 31st

The fire begun spreading northeastwards due to southwesterly winds. After 200 m, the fire front reached a pine forest with rocky ground and low understory vegetation, and with some patches of wetland. When the first rescue team arrived at 14:34, the left flank of the fire was burning with low intensity, and had an average flame height of about a meter. The right fire flank had reached a more dense and young pine forest located 600 m from the ignition point. Because of the higher intensity of this flank, the fire had climbed through the horizontal fuel continuity levels and reached the canopy (Länsstyrelsen i Västmanlands län 2014; MSB 2015).

Most of the day experienced winds of 5-8 m/s, but at 15:55 the wind velocity peaked at 10 m/s (SMHI 2014; MSB 2015). As a result of this, a rescue team that had managed to limit northeastwards fire growth were forced to retreat due to the heat from the approaching fire. Before they were forced to retreat, the team had extinguished about 400 m of the fire. The increased wind generated several fire spots and the rate of fire spread was assumed to vary across the region. 30 minutes later, the wildfire was estimated to be 2 km long and 500 m wide.

At 19:00, the Västmanland Fire reached a firebreak constituted by the small lake Öjesjön that is situated about 5 km northeast from the ignition point. The rate of fire spread decreased to 1-2 m/min during the night due to increasing relative humidity and extensive aerial firefighting of the left flank from 20:45, continuing for 1.5 h. Öjesjön marks the distance of fire spread during the first day that had been dry with less than 1 mm of precipitation (MSB 2015). The daily average temperature was 25 °C, and the relative humidity was between 40 and 50 % (SMHI 2014).

4.2.2 August 1st

From 5:00 in the morning of the 5th of August until around lunch, the Västmanland Fire was fought from the air with little noticeable effect. Like the previous day, the average daily temperature was 25 °C and the relative humidity was 40-50 %. The average wind was 3-6 m/s and directed towards northeast. Öjesjön was still blocking forward movement of the fire front while the flanks of the fire kept expanding. The left flak was slowly progressing northwestwards but was blocked before lunch between the northwestern part of Öjesjön and a small pond situated 1 km to the west, by a constructed barrier that was enhanced by aerial firefighting. A few hundred meters southwest of the ignition point, another barrier was built to prevent the slowly progressing rear fire from spreading southwest (MSB 2015).

During the same morning, the right flank had reached the bog Skennaren. The flank progressed southwards and around 12:00, a new fire head formed to the east of the bog as an extension from the main fire. An increased wind velocity of 12 m/s caused the new head to change direction and spread towards northeast with an average spread rate of 6 m/min. During the latter part of this distance, the canopy caught fire and the spread rate increased even more. The increased winds also generated spot fires to the north of the spread direction. Those proceeded north/northeastwards with the wind. After 3 km, the recently formed fire head that now represented the fire front got extinct when it reached a young spruce forest because of incombustible vegetation in the lower continuity levels. This spruce forest marks the eastern border of the total area that was affected by the Västmanland Fire (NASA FIRMS 2014; MSB 2015).

4.2.3 August 2nd

During the night between the 1st and 2nd of August, the wind direction changed from being southwesterly to southeasterly. This turned the approximately 5 km long and low intensively burning left flank from the days before, into a massive fire front. Because of the low intensity of the front, it took until after noon for it to significantly progress forwards. Around 13:30, several rescue teams had to retreat when the flames at the front quickly grew tenfold in height. Another consequence of the changed wind direction was that the barriers that were constructed the day before along the previously left fire flank, were broken (MSB 2015).

An extensive work to construct new barriers was carried out during the day. Northeast from the bog Kullmossen, located approximately 4.5 km north from the ignition point, was a 3 km long stripe of land heavily irrigated in an attempt to make the area incombustible. A part of this strip was also burned in a controlled way by the rescue services to reduce the available fire fuel. The barrier managed to hold most of the northwesterly progressing part of the fire front back, except the western part that formed a fire head when it found a narrow passage of 100-200 m between the western part of Kullmossen and the bog Högskovsmossen (MSB 2015). After 21:00, an additional fire head was formed at the westernmost part of the fire front. It was located roughly 2 km north of the ignition point (NASA FIRMS 2014; MSB 2015).

The weather during the 2nd of August was slightly warmer than that of the previous days with an average daily temperature of 29 °C and a relative humidity of 35-40 %. The wind peaked at 4-6 m/s, and was on average 1-4 m/s that day. As a result of the higher daily temperature, the relative humidity during the night between the 2nd and 3rd of August was lower than it had been during the recent nights (SMHI 2014; MSB 2015).

4.2.4 August 3rd

August 3rd experienced a similar weather as the day before except a higher relative humidity and around 5 mm of precipitation. Daily average temperature was 29 °C with an average relative humidity of 60 %. The average wind velocity was shifting between 2 and 6 m/s, and it was directed towards north/northwest. Some thunder was present with wind gusts peaking at 12 m/s, but no cloud-to-ground lightning was recorded (SMHI 2014; MSB 2015).

Fire intensity and spread rate was in general low that day due to the higher relative humidity that made the organic matter more resistant to fire. An almost 3 km long barrier was constructed during the afternoon at a location about 6 km northwest from the ignition point. It was a measure to stop the westernmost fire head that formed at 21:00 the evening before. The measure almost succeeded, but the head managed to brake through a 500 m long strip of the barrier during the evening. A bit earlier, a head formed as an extension from the north-eastern flank of the western part of the fire front when it was influenced by southwesterly winds. Those winds were generated by the suction force from the main fire that currently was on the northeastern side of Högskovsmossen. The deviating head continued towards the main fire during the night (MSB 2015).

4.2.5 August 4th

A high average temperature of 30-35 °C, an average relative humidity of 30 %, and an average southeasterly wind of 2-5 m/s with peaks around 12 m/s (SMHI 2014), made the 4th of August the day with the most favorable conditions for fire growth during when the Västmanland Fire was active. Despite the thick and black fire smoke that covered most of the area, six intensified fire heads were spotted on satellite imagery around 12:00. Two of those were represented by the two heads from the previous evening, and four were newly formed during this morning close to the northwestern and northeastern borders of the fire front. As the intensity increased, the heads became crown fires when they advanced upwards in the continuity levels (MSB 2015).

As the intensity increased during the day, it became too dangerous for the rescue services to operate at the fire front. Effort was instead put into limiting eastward, westward and southward fire spread. Spot fires were extinguished, and fires at the flanks and rear were fought. Backwards fire spread was for example limited to a few hundred meters (MSB 2015).

The favorable weather conditions allowed a vigorous convection plume to form above the fire, and which was fully developed at 15:38. The relative humidity dropped to 24 % due to the heat from the fire, and the wind velocity rose. This meant that the Västmanland Fire was influencing the local weather while intensifying itself. Between this time and 16:40, the northwestward fire spread rate peaked at 80 m/min, and when the fire expanded into the northern part of the region, it generated winds strong enough to fell healthy trees. The furious fire also generated a vast number of fire spots during the afternoon. Even on the opposite side of the lake Snyten were spots noted, which meant that burning matter had been transported up to 2 km by the winds (MSB 2015).

By the end of the day when the front reached the lake Snyten, the fire growth rate dropped drastically as a result of a lowering of the relative humidity, a weaker wind, and a more fire resistant vegetation. The area that had been raged by fire during this afternoon come to represent roughly three quarters (4 000 ha) of the total area that was affected by the Västmanland Fire (Land Survey of Sweden and SLU 2012; Länsstyrelsen i Västmanlands län 2014; MSB 2015). MSB (2015) stated after the fire, that there was no barrier within the region, nor any feasible measures that could have been taken, that had the potential to stop the massive northwestwards expansion of the Västmanland Fire during this day.

4.2.6 August 5th

The region experienced some thunder and light rainfall during the night, and which continued throughout the day. Average temperature was still high at around 29 °C, but the wind velocity had dropped to 1-3 m/s (SMHI 2014; MSB 2015). No notable fire expansion took place during the 5th of August, which was probably due to the high average relative humidity of 55-75%. Neither did the fire expand in the coming days meaning that the Västmanland Fire reached its maximum extent of roughly 13 000 ha during the 4th of August (Länsstyrelsen i Västmanlands län 2014; MSB 2015).

4.2.7 Impact on Regional Vegetation Briefly Summarized

Nilsson et al. (2014) estimated that 98 % of the approximately 9 600 ha forest was affected by fire. One fourth of the forest experienced fire in the canopy cover, and two fourths of the trees lost more than 50 % of their canopy leaves or needles due to thermal radiation. This meant that 917 000 m^3 of the forest was combusted or severely damaged by the Västmanland Fire. In terms of economic loss, the damage equals a cost of almost 1 billion SEK, or approximately 123 million USD and 110 million EUR (Länsstyrelsen i Västmanlands län 2014).

Chapter 5

Modelling Results

Two attempts where made to simulate fire growth as an endeavor to generate an area equivalent to that of the Västmanland Fire. The first attempt was performed by both FARSITE and Prometheus, and the data used came exclusively from SMHI (2014). After reviewing the results, it was noted that the wind velocity and direction from SMHI (2014) differed from the reported values by MSB (2015). A second attempt based on a combination of data from both SMHI (2014) and MSB (2015) was performed by Prometheus. Due to insufficient information, a second simulation could not be executed by FARSITE. Results from the both attempts are summarized in Table 5.1.

Table 5.1 clearly shows that the first attempt obtained a poor result by both FARSITE and Prometheus. FARSITE produced a burned region of 585 ha, out of which 530 ha were situated inside the Västmanland Fire boundary. That represents roughly 4 % of VF total. Prometheus generated an area five times larger than that of FARSITE. 78 % lay within the VF boundary. This represents 15.4 % of the real burned extent.

Simulation attempt 2 gave considerably better results. Prometheus produced an area almost two times larger than that of the final Västmanland Fire, and 41.9 % of the simulated predicted area was within the VF real extent. The following sections (5.1 and 5.2) presents the resulting maps (Figure 5.1–5.4), that were created when analysing the results. A more detailed review of the result from simulation attempt 2 is found in section 5.3. The modelled area is compared to daily growth (NASA FIRMS 2014) during the Västmanland Fire, and barriers found in section 4.2 are emphasized.

Table 5.1: Summary of results yielded by the two simulation attempts to regenerate an area similar to that of the Västmandland Fire. It is clearly seen that attempt 1 generated poor results, and that Prometheus simulated about 84 % of VF total in the second attempt. Insufficient data prevented FARSITE from running a second simulation.

VÄSTMANLAND FIRE (VF)		SIM. 1: SALA DATA		SIM. 2: MSB DATA	
Target Area: 13 096 ha		**FARSITE**	**Prometheus**	**FARSITE**	**Prometheus**
Simulated Area	(ha)	585	2 589	n.a.	26 097
Intersection with VF	(%)	90.9	78.0	n.a.	41.9
Extent VF Simulated	**(%)**	**4.1**	**15.4**	**n.a.**	**83.5**

5.1 Attempt 1: Poor Results

Figure 5.1 shows simulation 1 by FARSITE which yielded a small (radius 1.5 km) area that revolves the ignition point. It stretches towards north due to increasing altitude, while east and westward spread is restricted by two patches of non-fuel. A 400 m spread outside the VF boundary is seen in southwest. Closed timber litter (conifers) represents most of the burned vegetation.

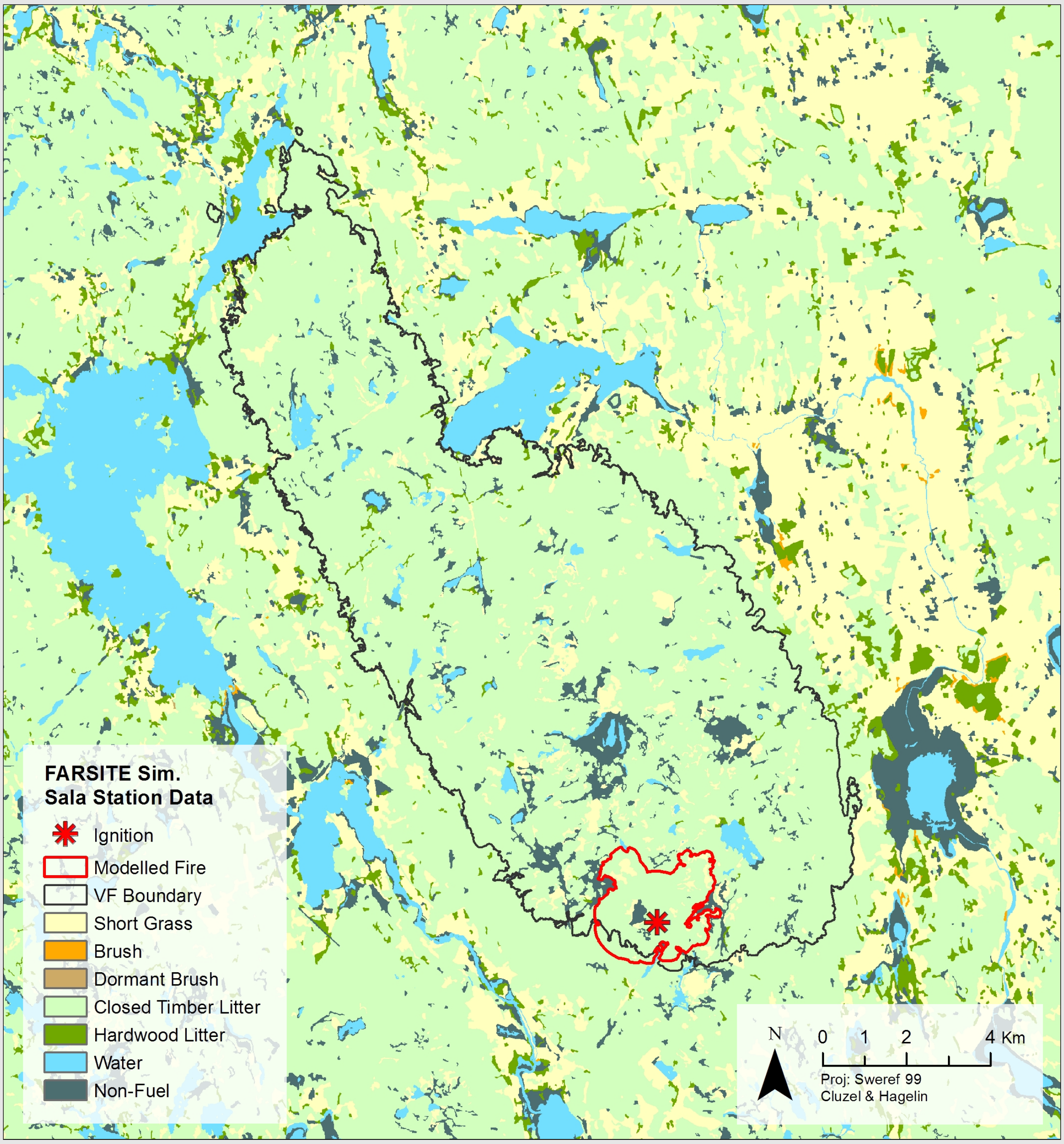

Figure 5.1: Simulation by FARSITE based on data from SMHI (2014). Compared to the Västmanland Fire boundary. Background shows reclassified regional vegetation.

Simulation 1 by Prometheus is displayed by Figure 5.2. The simulation resulted in a north-easterly offset circular area, whereof most of the spread occurred within a forested region. 4.5 km northeastwards spread was simulated, and the fire is seen to expand roughly 3 km southwestwards which means a 1.5 km spread outside the Västmanland Fire boundary in that direction. An additional branch of fire is extending towards southeast.

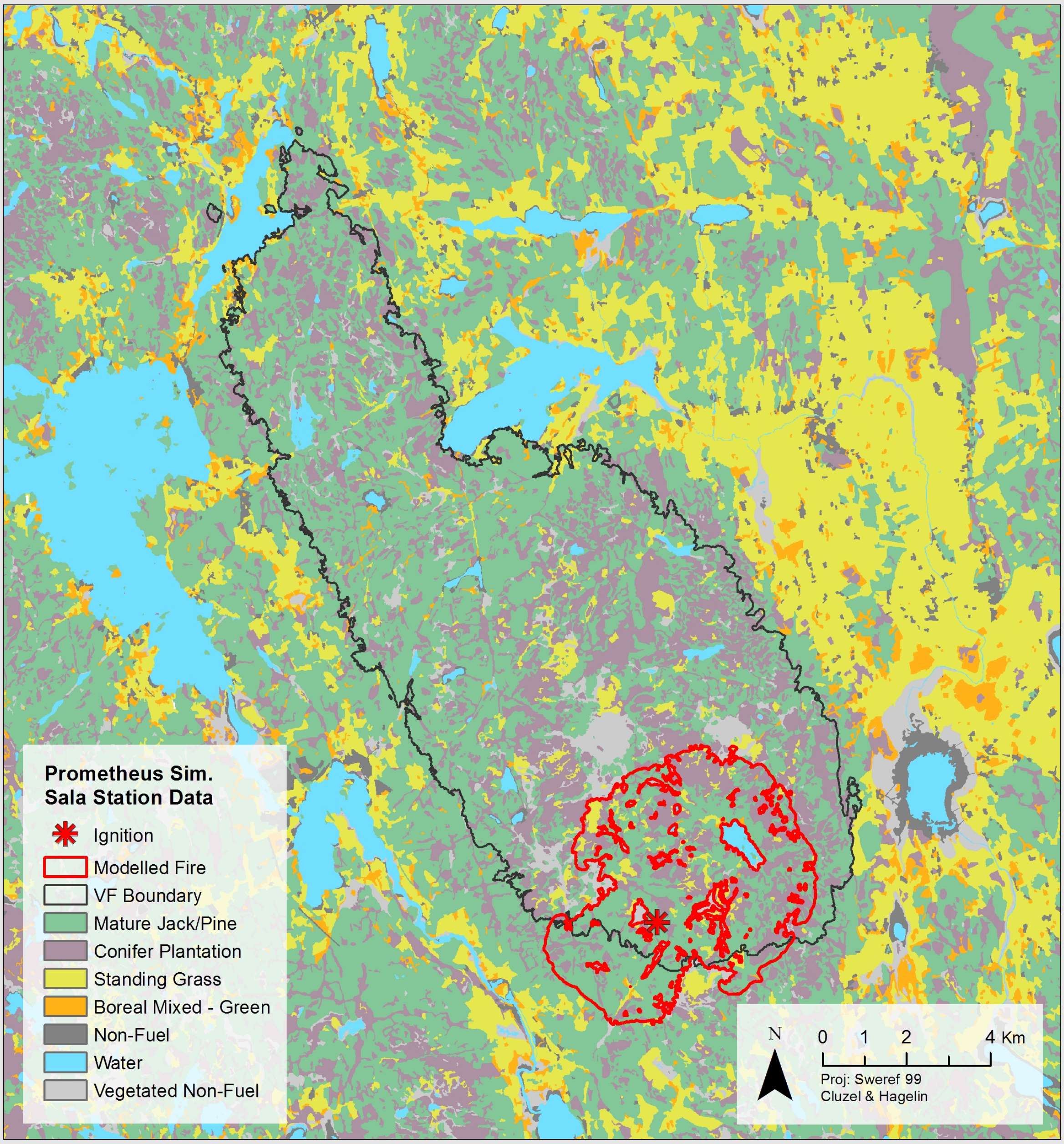

Figure 5.2: First simulation by Prometheus based on data from SMHI (2014). Compared to the Västmanland Fire boundary. Background shows reclassified vegetation in the studied region.

5.2 Attempt 2: Yielding Encouraging Results

Figure 5.3 shows a northwards stretching elongated area that was produced during the second simulation by Prometheus. The most prominent spread reaches 6 km outside the eastern VF boundary into grassy areas. Another distinguished spread reached the northwestern outer border, stopping the simulation at 14:55 on August 4. Patches of non-burned areas representing non-fuels are seen.

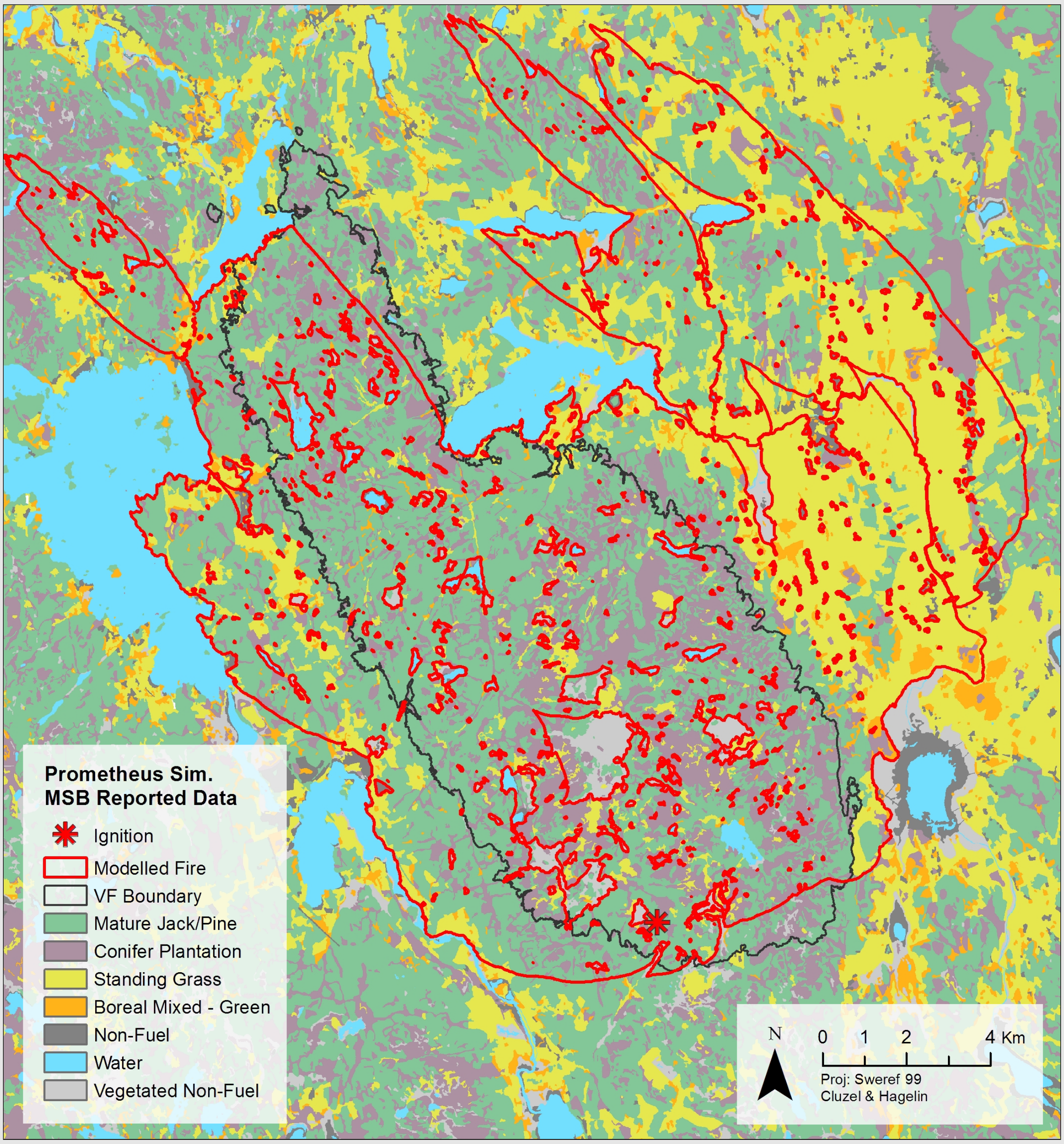

Figure 5.3: Attempt 2 by Prometheus based on data from SMHI (2014) and MSB (2015). Compared to the Västmanland Fire boundary. Better results than attempt 1 (see Figure 5.2).

A visual day-by-day comparison between the modelled fire growth during the second simulation by Promethus and reference points (NASA FIRMS 2014) is presented by Figure 5.4. Some reference points are located outside the VF Boundary which are explained by MSB (2015) as distance spotting. The simulated fire growth coincides with the daily reference, except from the vast north-northeastwards over prediction that occurred on August 1st.

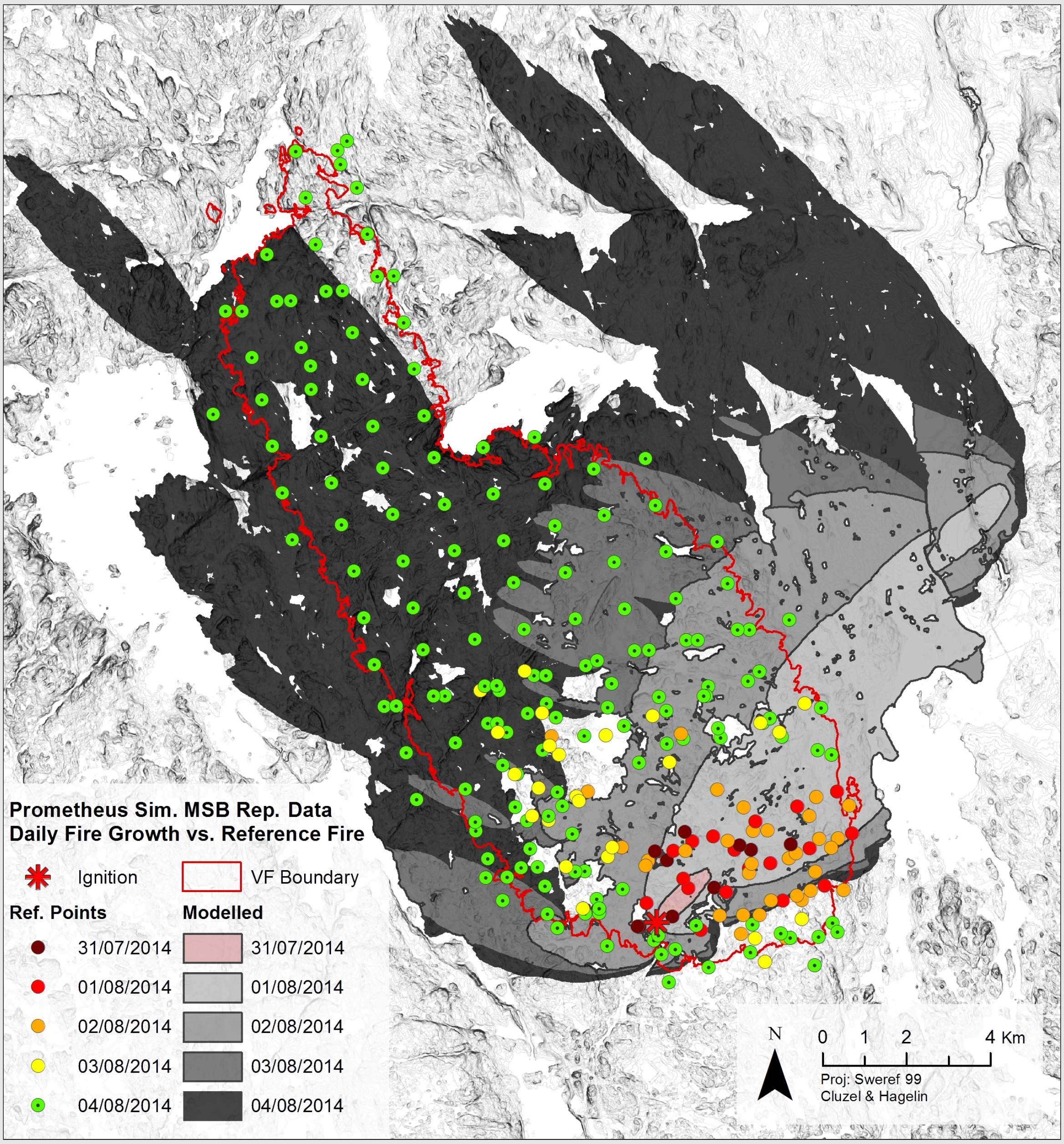

Figure 5.4: Day-by-day comparison between predicted spread by Prometheus and the ground reference (MSB 2015). Simulation matches the real spread, but generates an over estimation towards northeast, west and northwest.

5.3 Barriers to Fire Growth

Several barriers constructed by the Swedish rescue services were identified in section 4.2. Those are added manually to Figure 5.5 at estimated locations since their exact spatial position is unknown. It is seen that the over prediction made by Prometheus to northeast could have been limited if barriers were simulated. An additional natural barrier is stressed in section 6.1.2.

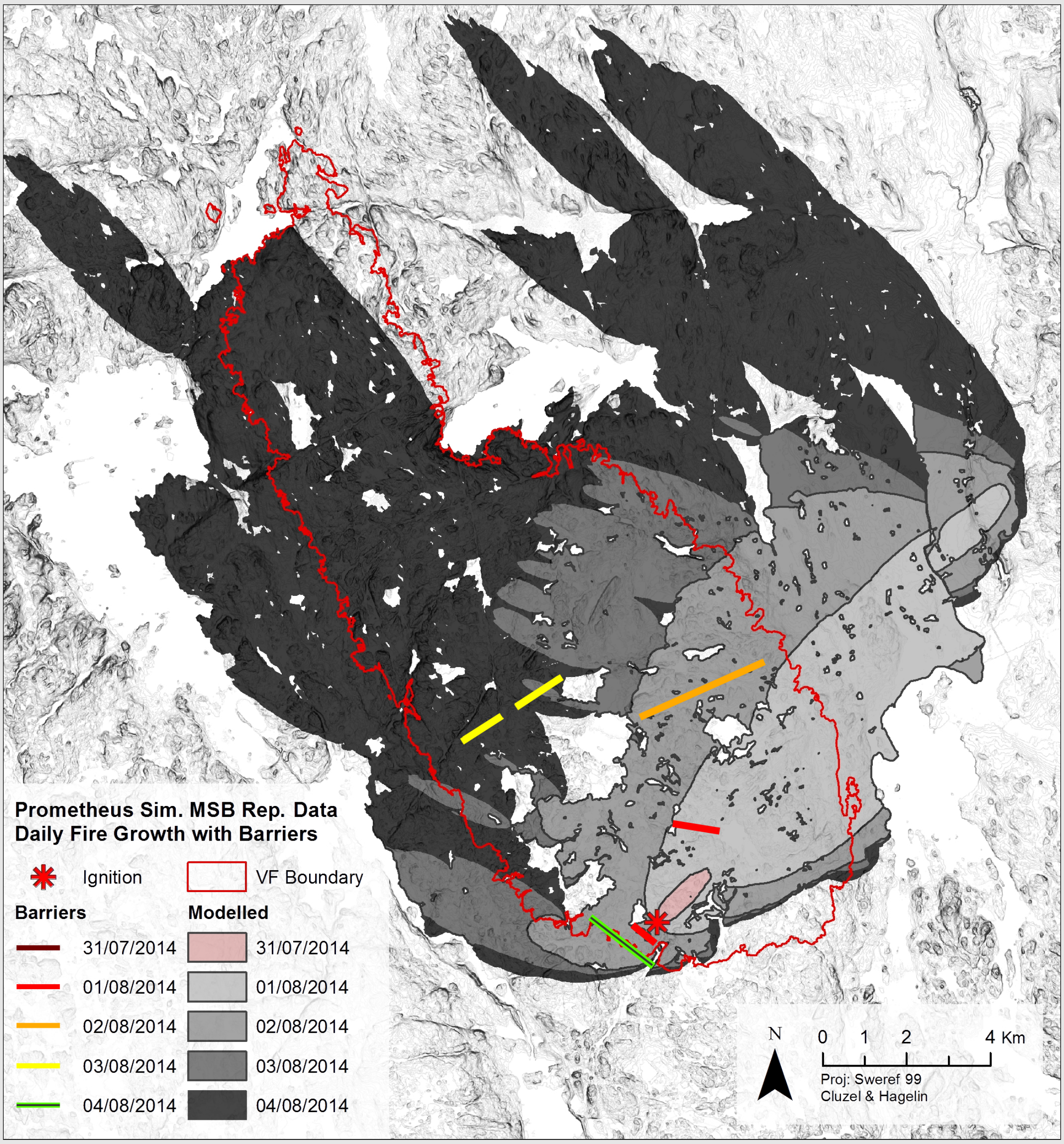

Figure 5.5: Manually added and estimated barriers caused by firefighting that could have limited the northeastward overestimation by Prometheus. Interpreted in section 4.2.

Chapter 6

Discussion

This chapter covers the interpretation of the modelling results. It also includes an evaluation of model usability where pros and cons of FARSITE and Prometheus are discussed (section 6.1). The final section (6.2) stresses the need for future studies, and contains recommendations to consider before running further simulations.

6.1 Model Suitability Evaluation

Section 5.1 shows that both FARSITE and Prometheus failed to reproduce the final extent of the Västmanland Fire during their first run. Though, when evaluating the results, based on the information in section 4.2, it became evident that the wind inputs taken from SMHI (2014) were different from those reported by MSB (2015). This led to the creation of a new weather data set that were used in the second attempt. Simulation attempt 2 is thoroughly reviewed in section 6.1.2. A more brief evaluation of the results is found in section 6.1.1, while section 6.1.3 contains an usability assessment of the two models.

6.1.1 Fire Growth Simulation

A reason to why the simulated area by FARSITE is smaller than that of Prometheus can be derived from the different initial moisture content inputs to the applications. When the initial moisture content input was prepared for FARSITE, it was approximated due to the lack of data. This may have caused a smaller predicted burned area since the fuel moisture has a major effect on ignition and fire spread as seen in section 2.1. Another reason can be the way in which the applications interpolate weather data. FARSITE treats the wind parameter as constant over a region, while Prometheus creates a wind profile relative to the elevation.

FARSITE and Prometheus use different fuel type models meaning that areas having similar fuel type classification might be combusted differently due to algorithmic variations. This should have a noticeable effect on rate of fire spread. It is however difficult to evaluate since the modelled outputs show other visual differences than just the extent. When comparing Figure 5.1 and 5.2, it is obvious that Prometheus generated patches of non-burned areas within the modelled region. The reason to why FARSITE did not generate similar patches is unknown but could be explained by that the model only shows the outer perimeter of the predicted extent, and simply hides generated unburned patches.

Both models produced circular areas which were much smaller than the final Västmanland Fire boundary, as seen in Figure 5.1 and 5.2. It is presumed that these small shapes most likely are a result of the low average wind velocities that were used as input in attempt 1 (see Appendix B). If these forms were related to structural differences between the models, more distinctive characteristics would have been denoted. These poor results indicated the need of a revised wind data set, and section 4.2 confirms that the data set needed revision since the wind data from SMHI (2014) did not match the weather situation in the Västmanland Fire affected region.

Attempt 2 was carried out by Prometheus alone because of the inability of FARSITE to work with the low amount of wind data interpreted from MSB (2015). Figure 5.3 shows the considerably better and more promising result of attempt 2, compared to the results from the first set of simulations, though it is apparent that the model over-predicted the extent of the burned region. It is also seen that the simulation reached the northwestern border of the studied area meaning that the prediction stretched further than 5 km away from the Västmanland Fire. These findings are further discussed in the following section (6.1.2).

6.1.2 In Depth Review of Promising Results

Simulation two by Prometheus was interrupted when the modelled spread reached the allowed spatial limit in the northwestern part of Figure 5.3. The interruption occurred around 15:00 on the 4th of August, just when the intensity of the Västmanland Fire had reached its climax as described in section 4.2.5. This indicates a higher rate of fire spread than that of the real fire since the simulated fire reached the lake Snyten before the evening of August 4th. Furthermore, section 2.1.2 explains that spread rate is highly induced by wind velocity, meaning that this higher spread rate could be caused by the lack of temporal input for the model. Occasions of high intensity wind events were reported between 15:38 and 16:40, and which cannot be reproduced by Prometheus since the model creates a sinusoidal function when it interpolates the wind profile.

When comparing the daily predicted fire growth and the reference points in Figure 5.4, it is seen that the over-prediction that began on the 1st of August laid the foundation for the consecutive over-prediction that covered most of the northeastern part of the study area. Figure 5.5 shows the same prediction as Figure 5.4, but with manually added anthropogenic barriers from section 4.2. These could not be included in the simulation without knowing their exact spatial location and fire intensity resistibility, but it is likely that these barriers would have reduced the over-prediction. Modelled spread in areas without barriers, such as the spread that stretches north-northwest from the ignition point, shows a conformity with the reference points that supports the assumption of a satisfying prediction. However, Figure 5.5 only shows barriers of anthropogenic origin and thus omits the natural barrier that caused the extinction of the eastern front of the Västmanland Fire on August 1st. The reason to why the fire got extinct is unknown (MSB 2015), but proves that the fuel type classification failed in this region and explains the vast over-prediction to northeast.

6.1.3 Model Assessment

To conduct a fair comparison of the models, it was decided to run them using only their required inputs. This gave a rough estimate of the workload needed to quickly generate results. Both models were rather easy to set up, except for the initial moisture content input that was problematic to obtain. It is assumed that the outputs would be improved by using optional inputs, but at the expense of response time that can be crucial in case of a forest fire. Prometheus has a more polished user interface than FARSITE and is thus perceived as the most user-friendly application. The model is flexible in terms of inputs since it deals with inconsistent data, and has the ability to interpolate for example slope and aspect. FARSITE requires more inputs before allowing a simulation to start as explained in section 2.2. In terms of exported results, Prometheus generated a detailed shapefile containing the daily extent during the simulation, while FARSITE resulted in an un-projected final outer perimeter. Another advantage of Prometheus is its COM-structure (see section 2.3.2) that allows exportation of its modules meaning that it could be a great base for the development of a fire growth simulation model suitable for application in a Swedish environment.

6.2 Final Thoughts

Some aspects of the applications have to be improved as neither of the standard NFFL fuel models nor the FBP System contains classes that fully represents the vegetation types found in the studied region. For example wetlands had to be reclassified as non-fuels, which should cause errors since wildfires can spread over such areas. This implies that there is a need for the development of custom fuel models before a model could be fully adapted for use in Sweden. Also, inconsistent data and a weak interpolation were the result of using only one weather station, and which explains why simulation attempt 1 yielded poor results as seen in section 5.1. Using more weather stations would likely have increased the accuracy of the results, though data from only one nearby weather station were available. This should however not be an issue during an ongoing fire since the weather input most likely would be constituted by weather forecasts, meaning that the input would appear as a raster instead of point sources.

The study has shown that Prometheus has a better potential than FARSITE for application in Sweden. Though, the results should not be considered as a confirmation of suitability as only one reference fire was used when testing the applications. Before a model can be recommended to the authorities in Sweden as a measure against forest fire growth, more testing on other fires have to be carried out.

Chapter 7

Conclusion

Overall, the work has been encouraging and simulation attempt 2 managed to model roughly 80 % of the Västmanland Fire despite using only mandatory inputs and non-ideal data sets. In spite of this, none of the tested models are suitable for Sweden in their current state. Therefore should the study be seen as a first stage of a larger project that intends to provide a fire growth simulation model suitable for a Swedish environment. The following need to be considered in future studies:

- Prometheus COM-structure constitutes a solid foundation for the development of a Swedish fire growth simulation model since it is versatile and offers substantial customization.
- A clear methodology of how to determine initial moisture content of forest fire fuels, and a fuel type classification scheme customized for Swedish flora and fauna need to be worked out in order to increase simulation accuracy.
- Barriers caused by rescue services should be implemented in a simulation as they can prevent over-prediction of fire growth vastly.

Prometheus proved to have greater potential for application in Sweden as it yielded better results than FARSITE. Though, a successful simulation of one reference fire is not sufficient to confirm suitability. More studies are required where simulation of additional forest fires are evaluated before a model can be suggested to the Swedish authorities as a measure against forest fire spread.

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Appendix A

Detailed Reclassification of Vegetation

Full reclassification of the vegetation documented by Land Survey of Sweden and SLU (2012) is shown in Table A.1 The original classification is seen in columns one and two.

Table A.1: Original vegetation types retrieved from Land Survey of Sweden and SLU (2012) and the reclassification for both models.

Value	Vegetation Type	FARSITE Type	Value	Prometheus Type	Value
110	Öppet vatten	Water	98	Water	102
111	Grunda bottnar	Water	98	Water	102
112	Periodisk vattensamling	Water	98	Water	102
120	Vattenvegetation (ospec)	Non-Fuel	99	Non-Fuel	101
200	Öppen substratdominerad mark	Non-Fuel	99	Non-Fuel	101
210	Hällmark	Short Grass	1	Standing Grass	32
310	Kulturmark	Short Grass	1	Standing Grass	32
311	Åker/vall	Short Grass	1	Standing Grass	32
312	Kultiverad gräsmark	Short Grass	1	Standing Grass	32
314	Igenväxt och planterad kulturmark	Short Grass	1	Standing Grass	32
315	Skogsplanterad f.d. öppen mark	Closed Timber Litter	8	Conifer Plantation	6
317	Odlad busk- och trädmark	Dormant Brush, Hardwood Slash	6	Unknown Non-Fuel	103
321	Bebyggelse/tomtmark	Non-Fuel	99	Non-Fuel	101
323	Gräsmatte-, park- och tomtmark	Short Grass	1	Standing Grass	32
330	Exploaterad mark	Non-Fuel	99	Non-Fuel	101
441	Torr gräs-örtveg	Short Grass	1	Standing Grass	32
444	Frisk gräs-örtveg	Short Grass	1	Standing Grass	32
445	Fuktig gräs-örtveg	Short Grass	1	Standing Grass	32
446	Fuktig-våt gräs-örtveg	Short Grass	1	Standing Grass	32
454	Sötvattensstrandäng (nordlig)	Non-Fuel	99	Vegetated Non-Fuel	105

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Table A.1 – Continued from the previous page

Value	Vegetation Type	FARSITE Type	Value	Prometheus Type	Value
522	Videbuskveg	Brush	5	Standing Grass	32
610	Barrskog, ospec	Closed Timber Litter	8	Conifer Plantation	6
615	Hällmarksbarrskog	Closed Timber Litter	8	Conifer Plantation	6
620	Barrskog på tunt jordtäcke	Closed Timber Litter	8	Conifer Plantation	6
625	Lavmarksbarrskog	Closed Timber Litter	8	Conifer Plantation	6
633	Torr barrskog	Closed Timber Litter	8	Conifer Plantation	6
635	Frisk barrskog (ej lavrik)	Closed Timber Litter	8	Mature Jack or Lodgepole Pine	3
636	Frisk-fuktig barrskog	Closed Timber Litter	8	Conifer Plantation	6
637	Fuktig barrskog	Closed Timber Litter	8	Conifer Plantation	6
641	Våt barrskog	Closed Timber Litter	8	Conifer Plantation	6
642	Våt barrskog och myrbarrskog	Closed Timber Litter	8	Conifer Plantation	6
643	Barrskogsmyr	Closed Timber Litter	8	Conifer Plantation	6
710	Lövskog, ospec	Hardwood Litter	9	Boreal Mixedwood - Green	50
720	Lövskog på tunt jordtäcke	Hardwood Litter	9	Boreal Mixedwood - Green	50
734	Torr-frisk lövskog	Hardwood Litter	9	Boreal Mixedwood - Green	50
737	Fuktig lövskog	Hardwood Litter	9	Boreal Mixedwood - Green	50
741	Våt lövskog	Hardwood Litter	9	Boreal Mixedwood - Green	50
742	Våt lövskog och lövskogsmyr	Hardwood Litter	9	Boreal Mixedwood - Green	50
743	Lövskogsmyr	Hardwood Litter	9	Boreal Mixedwood - Green	50
760	Blandad ädellövskog, ospec	Hardwood Litter	9	Boreal Mixedwood - Green	50
761	Ekskog	Closed Timber Litter	8	Boreal Mixedwood - Green	50
800	Öppen myrvegetation (ej skogsbevuxen)	Non-Fuel	99	Vegetated Non-Fuel	105
810	Ristuvemyr	Short Grass	1	Standing Grass	32
820	Fastmattemyr	Short Grass	1	Standing Grass	32
823	Fastmattekärr, högstarrvariant	Non-Fuel	99	Vegetated Non-Fuel	105
830	Mjukmattemyr	Non-Fuel	99	Vegetated Non-Fuel	105
840	Lösbottenmyr	Non-Fuel	99	Vegetated Non-Fuel	105

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Table A.1 – Continued from the previous page

Value	Vegetation Type	FARSITE Type	Value	Prometheus Type	Value
843	Lösbottenkärr, brunmossvariant	Non-Fuel	99	Vegetated Non-Fuel	105
850	Mjuk-fastmattemyr	Non-Fuel	99	Vegetated Non-Fuel	105
860	Högstarr-sumpkärr	Non-Fuel	99	Vegetated Non-Fuel	105
861	Högstarrkärr	Non-Fuel	99	Vegetated Non-Fuel	105
862	Sumpkärr	Non-Fuel	99	Vegetated Non-Fuel	105
871	Videkärr	Non-Fuel	99	Vegetated Non-Fuel	105

Appendix B

Weather Data Inputs

Weather data from SMHI (2014). Used by both models.

Table B.1: Wind data used as input for FARSITE.

Day	Temp_{min} (℃)	Temp_{max} (℃)	R.H._{min} (%)	Prec (mm)	Wind_{min} (m/s)	Wind_{max} (m/s)	Wind Dir (°)
28/07/2014	13.2	28.7	41	0	0	12	296
29/07/2014	14	28.2	39	0	0	9	253
30/07/2014	14.2	26.2	64	8.4	0	10	189
31/07/2014	15.3	24.6	37	0.2	0	17	223
01/08/2014	12.2	24.2	37	0	0	22	225
02/08/2014	10.1	27.3	36	0	0	5	290
03/08/2014	17.3	28.8	56	0.6	0	6	60
04/08/2014	17.8	34.4	27	0	0	6	64
05/08/2014	16	27	58	3.7	0	4	6
06/08/2014	16.3	21.1	82	1.5	0	8	330
07/08/2014	15.5	24.7	49	1.8	0	9	289

Table B.2: Wind data used as input for FARSITE.

Month	Day	Prec (mm)	Hour1 (min)	Hour2 (min)	Temp_{min} (℃)	Temp_{max} (℃)	R.H._{max} (%)	R.H._{min} (%)	Elev (m)
7	28	0	400	1600	13	29	97	41	60
7	29	0	400	1600	14	28	97	42	60
7	30	840	400	1600	14	26	97	64	60
7	31	20	400	1600	15	25	88	37	60
8	1	0	400	1600	12	24	94	37	60
8	2	0	400	1600	10	27	95	37	60
8	3	60	100	1600	17	29	90	60	60
8	4	0	100	1300	18	34	96	27	60
8	5	370	400	1300	16	27	97	58	60
8	6	150	400	1600	27	21	98	82	60
8	7	180	400	1600	16	25	98	49	60

Table B.3: Weather data excluding wind. Used as input for FARSITE.

Month	Day	Time (min)	Wind Velocity (m/s)	Wind Dir (°)	Cloud Cover (%)
7	28	100	0	0	0
7	28	400	0	0	0
7	28	700	0	0	0
7	28	1000	4	204	0
7	28	1300	10	213	0
7	28	1600	12	232	0
7	28	1900	9	253	0
7	28	2200	0	0	0
7	29	100	5	230	0
7	29	400	0	0	0
7	29	700	0	0	0
7	29	1000	9	257	0
7	29	1300	7	274	0
7	29	1600	2	233	0
7	29	1900	2	194	0
7	29	2200	3	201	0
7	30	100	0	0	0
7	30	400	0	0	0
7	30	700	3	182	0
7	30	1000	6	177	0
7	30	1300	10	206	0
7	30	1600	3	176	0
7	30	1900	5	189	0
7	30	2200	4	188	0
7	31	100	4	202	0
7	31	400	3	198	0
7	31	700	14	242	0
7	31	1000	17	232	0
7	31	1300	17	250	0
7	31	1600	14	230	0
7	31	1900	11	234	0
7	31	2200	4	192	0
8	1	100	6	208	0
8	1	400	2	115	0
8	1	700	12	221	0
8	1	1000	15	238	0
8	1	1300	17	232	0
8	1	1600	22	227	0
8	1	1900	6	236	0
8	1	2200	0	0	0
8	2	100	3	199	0
8	2	400	0	0	0

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Table B.3 – Continued from the previous page

Month	Day	Time (min)	Wind Velocity (m/s)	Wind Dir (°)	Cloud Cover (%)
8	2	700	0	0	0
8	2	1000	4	163	0
8	2	1300	4	193	0
8	2	1600	5	186	0
8	2	1900	0	0	0
8	2	2200	0	0	0
8	3	100	0	0	0
8	3	400	0	0	0
8	3	700	3	108	0
8	3	1000	0	0	0
8	3	1300	6	115	0
8	3	1600	5	122	0
8	3	1900	2	149	0
8	3	2200	0	0	0
8	4	100	0	0	0
8	4	400	0	0	0
8	4	700	0	0	0
8	4	1000	3	121	0
8	4	1300	6	130	0
8	4	1600	6	140	0
8	4	1900	3	128	0
8	4	2200	0	0	0
8	5	100	0	0	0
8	5	400	0	0	0
8	5	700	0	0	0
8	5	1000	4	351	0
8	5	1300	2	119	0
8	5	1600	0	0	0
8	5	1900	0	0	0
8	5	2200	2	192	0
8	6	100	0	0	0
8	6	400	0	0	0
8	6	700	7	360	0
8	6	1000	0	0	0
8	6	1300	8	222	0
8	6	1600	5	257	0
8	6	1900	5	294	0
8	6	2200	0	0	0
8	7	100	4	252	0
8	7	400	0	0	0
8	7	700	0	0	0
8	7	1000	0	0	0

Continued on the next page

Table B.3 – Continued from the previous page

Month	Day	Time (min)	Wind Velocity (m/s)	Wind Dir (°)	Cloud Cover (%)
8	7	1300	9	283	0
8	7	1600	5	259	0
8	7	1900	9	240	0
8	7	2200	6	230	0

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