ANALYSIS OF FLUID-MECHANICAL EFFICIENCY OF OFFSHORE WIND TURBINES FROM REGIONAL TO LOCAL SCALE

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Abstract

Renewable energy resources, such as wind, are available worldwide. Locating areas with high and continual wind sources are crucial in pre-planning of wind farms. Vast offshore areas are characterized with higher and more reliable wind resources in comparison with continental areas. However, offshore wind energy production is in a quite preliminary phase. Elaborating the potential productivity of wind farms over such areas is challenging due to sparse in situ observations. Mediterranean basin is not an exception. The overall aim of this thesis is to perform analysis in model efficiency in estimation of wind energy from regional to local scale.

First, we are proposing numerical simulations of near-surface wind fields from regional climate models (RCMs) in order to obtain and fill the gaps in observations over the Mediterranean basin. Four simulations produced with two regional climate models are examined. Remote sensing observations (QuikSCAT satellite) are used to assess the skill of the simulated fields. A technique in estimation the potential energy from the wind fields over the region is introduced locating the three potentially interesting sub-regions for wind farms.

Then, we use local-scale model (large-eddy simulation) with implemented parameterization of wind turbine in order to simulate real case flow in theoretical wind farm. Information reported with regional climate model would be used to create inflow conditions for the selected sub-region of the Mediterranean Sea for simulating theoretical offshore wind farm.

Finally, we would compare the estimation of wind power potential obtained by regional climate model and power production of theoretical wind farm obtained with large-eddy simulations for chosen sub-region. Within this multi-scale approach, we would present different numerical computational efficiency in application of wind energy and justification in usage of both regional and local scale models. The novelty of this multi-model methodological approach could be considered in offering significant information for wind industry.
Abstract in Italiano

Le risorse energetiche rinnovabili, come il vento, sono disponibili in tutto il mondo. Individuare le zone con un’alta concentrazione ventosa ma soprattutto con una certa costanza nell’arco dell’anno è un buon punto di partenza per la progettazione e installazione di parchi eolici. Vaste aree off shore sono caratterizzate da risorse eoliche più alte e più affidabili rispetto alle aree continentali. Tuttavia, la produzione di energia eolica off shore è in una fase molto preliminare. Prevedere il potenziale di produttività di impianti eolici su tali aree è difficile a causa dei pochi dati di osservazioni che si hanno a disposizione; discorso valido anche per il Bacino del Mediterraneo. L’obiettivo principale di questa tesi è di dimostrare l’affidabilità di un modello su scala locale da un modello su scala regionale per la stima di produzione di energia da un parco eolico.

In primo luogo, vengono effettuate simulazioni numeriche di flussi ventosi in prossimità di superfici, basandosi su modelli climatici regionali (RCM), al fine di ottenere maggiori osservazioni sul bacino del Mediterraneo. Sono state effettuate quattro simulazioni utilizzando due modelli climatici regionali. Per valutare la validità delle zone simulate vengono utilizzati dati ottenuti mediante telerilevamento satellitare (QuikSCAT). I dati ottenuti, di produzione di energia eolica prodotta utilizzando modelli climatici regionali, vengono utilizzati per individuare tre sotto-regioni potenzialmente interessanti dove installare parchi eolici. Dopo viene utilizzato un modello su scala locale (large-eddy simulation) con parametrizzazioni implementate con turbine eoliche al fine di simulare il flusso ventoso reale in un parco eolico teorico. Per la simulazione di un parco eolico off-shore potrebbero essere usate, per creare le condizioni di flusso, le informazioni ottenute con il modello climatico regionale. Infine, si vuole confrontare la potenza prodotta da un campo eolico teorico situato nella sub-regione prescelta utilizzando sia il modello climatico regionale che il modello su scala locale. All'interno di questo approccio multi-scala, si vogliono presentare differenti metodi di efficienza numerica computazionale
per giustificare l’utilizzo sia di modelli su scala regionale che di modelli su scala locale. La novità di questo approccio metodologico multi-model potrebbe essere presa in considerazione dall'industria eolica per ottenere utili informazioni.
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Introduction

The topic of offshore wind energy is quite broad and encompasses various technologies and needs expertise from many fields of engineering to economics, environmental impact, meteorology and climatology. In this thesis we would like to gain information for wind industry by using regional climate and local scale models to localize sub-regions with high wind energy potential over Mediterranean Sea.

The Mediterranean Sea is located in the mid-latitudes stretches from the Atlantic Ocean on the west to Asia on the east and separates Europe from Africa. The basin is almost entirely surrounded by mountain chains, which creates an interesting climatic system by itself. Complex orography and land-sea interaction of a basin are suitable for formation of persistent local winds whose occurs on a various time scales. Mediterranean region is characterized with high density in its population. Due to high density of population of surrounding countries the region have a high energy market being placed of about 9% of entire world’s energy demand. By 2020 European Union have a strategy to produce 20% energy from renewable sources from its entire energy demand. With the facts of prevailing winds and demographic situation of surrounding countries, Mediterranean Sea is placed as a possible region in harvesting the wind.

Renewable energy is only in the initial phase of exploitation in the Mediterranean countries in spite of consistent potential especially offshore wind. Up to now no offshore wind farms are operating in Mediterranean waters. A prototype wind turbine has been installed in the Gulf of Lion in French waters since 2014. Installation of first offshore wind farm in the Mediterranean Sea near the French coastline should start in 2015 and end of project is expected in 2018. Similar project were active in the coasts of Spain and Italy. Italian project started with a prototype in 2008 in the Southern Adriatic Sea, but up to now no offshore wind farms have been installed yet.

The overall aim of this thesis is to develop accurate and robust analysis of current and available state of-the-art models for offshore applications. We firstly use regional climate models to map the regional resources and to select location of interest for further assessment. Then, large eddy simulations were performed simulating the information gained from regional climate model output to obtain high resolutions estimations for wind energy assessment. Further, parameterization of wind turbine was introduced and implemented into the large eddy simulations for theoretical offshore wind farm. Finally, we present preliminary estimation of theoretical offshore wind farm if being placed at sub-regions selected by regional climate models. It should be noted that regional climate models and large eddy simulations have been
generally used for quite different topics. Altogether methodology should be considered offering significant information for wind industry.

The research activity for proposes of this thesis was done in collaboration with University of Trieste and C.R. ENEA Cassaccia, technical unit UTMEA. A first task considered regional analysis and entire work was done in ENEA. Second part of research consisted of usage of large eddy simulation numerical model and its application and parameterization of wind turbines were performed at University of Trieste, Dipartimento di Ingerneria ed Architettura and collaboration with its spinoff IE-FLUIDS.

This thesis is structured as follows: the information about current image of wind energy in Europe, general characteristic of wind and estimation of wind potential are reporter in Chapter 1. Also in the following Chapter there would be introduced a region of interest. In Chapter 2 regional climate analysis is presented. Four simulations of two different regional climate models are here presented in terms of their capability in representing wind speed compared and validated against satellite observations. Starting from these results we select potential sub-regions for wind farms over the region of interest. The local results are implemented in Chapter 3 where large eddy simulation is performed and wind turbines are added in simulations. Chapters 2 and 3 possess separate sub-conclusions, where main conclusion is followed as separate sub-section with discussion for entire thesis and ideas for future work.
Chapter 1

This Chapter is divided in two parts. First part involves shortly history and current stage of Europe’s offshore technology. In the second part physical characteristics of wind and estimations of available power gained from the wind are presented. The region of interest is the Mediterranean Sea, and its characteristic wind regimes are also shortly described.

1.1 Wind energy in Europe

The renewables industry encourages technological innovation contributed with expertise from many fields of engineering to economics, material science, environmental impact, meteorology and climatology. Renewable energy comes from sources such as sun, wind, ocean and plants. Those sources of energies do not deplete over years and are an essential alternative to fossil fuels.

In the middle of 1970s begins an oil embargo, causing oil prices to rise dramatically. High oil prices increase interest in alternative energy sources. This called for different energy application and renewable sources. Public concern about environmental issues such as climate change encourage interest in 1990s and governments take an interest in using renewable energy as a way to decrease greenhouse gasses and other emissions. A country or region where energy production is based on imported coal or oil will become more self-sufficient by using alternatives where such one is power from the wind. Energy produced from the wind produces no emissions connected with the contribution to the greenhouse effect.

The force of the wind has been used since many centuries. It is proven to be a source of clean, affordable and renewable energy started to be interesting again at the end of the 20th century. The wind resources are widely available with many parts of the world having areas with high average wind speeds onshore and offshore [1]. From an idea to convert energy from the wind until the installation of wind farms many tasks needs to be solved. One of initial problems is locating potential available wind resource and final to resolve management issues for finalizing the project.

1.1.1 The idea of off-shore wind farms

Offshore wind energy, as the name implies, refers to electricity produced by wind
turbines that are installed offshore and implicitly in the ocean (or in seas and lakes). Offshore wind farms are at the beginning of their commercial deployment stage. In 2002 and 2003, the first large, utility-scale offshore farms were commissioned with higher capital costs than onshore. Abundant wind resource offshore is one of the key factors that make offshore wind energy attractive. Offshore wind installations could have electricity outputs 50% larger than equivalent onshore wind farms. Ten kilometers from the shore, speeds may be 25% higher than at the coast [1; 2; 3]. Winds over open water are invariably higher, exhibit a less shear and are intrinsically less turbulent than over adjoining land. The higher the wind speeds, implies the higher productivity. Lower wind shear also means that tower height can be less high offshore than in often necessary on land. On positive side, wind turbines generally perform better in less turbulent winds. On the other hand, less turbulence means that downstream wakes take longer to recover than when the winds are more turbulent. Thus, spacing between wind turbines should be higher offshore than it would be on land. Higher wind speeds, lower wind shear and lower turbulence are related phenomena and arise because the water surface is much smoother than the land. This smoothness appears in the physics of the wind through the surface roughness. In contrast to the land, however, surface roughness of the water may change with time. The changes in the surface roughness parameter would be discussed further in Chapter 3.

Wind energy has become one of today’s lower cost renewable energy technologies in terms of the cost per kWh of electricity generated. Nevertheless, energy from the wind can only be produced when nature supplies sufficient wind. The knowledge in advantage of the resources available in the near future could permit an adaptation of conventional power farms to a changed climate. The installation of wind farms requires a significant amount of planning and coordination. Mistakes can be very costly. Before wind turbines can be installed and connected to an electrical grid, the exact location for the future turbines need to be determined. A primary consideration is maximizing energy capture. Finding the offshore locations with reliable and constant wind energy is not an easy task.

Wind energy development has both positive and negative environmental impacts. On the positive side, wind energy is generally regarded as environmentally friendly while impacts such as visual impact, land/sea-use and bird interaction with wind turbines holds for negative environmental impacts. For the design of wind turbine on land, the primary external condition to consider is the wind itself. In the case of offshore wind farm, however, additional conditions such as waves, sea bathymetry, the marine environment and the sea life need to be considered. There are some challenges as well; higher project costs due to a necessity for specialized installation and service vessels and equipment and more expensive support structures; more difficult working conditions; more difficult and expensive installation procedures; decreased availability due to limited accessibility for maintenance; necessity for special corrosion prevention measures [1]. A discussion of these topics is beyond the scope of this thesis. Here
only the primary condition as wind resources over the sea would be considered.

1.1.2 Offshore wind farms in Europe

The European Union aims to get 20% of its energy from renewable sources by 2020. The exploitation of renewable energy sources can help the EU to meet many of its environmental and policy goals to reduce greenhouse emissions and to make it less dependent on imports of fossil fuels. Wind energy currently meets 3.7% of EU electricity demand. EWEA, the European Wind Energy Association, is actively promoting wind power in Europe and worldwide. Wind power sector has grown exponentially in recent years. EWEA projections suggest that the wind power sector will continue to fast grow. The European Commission’s goal of increasing that share to 12% by 2020 is regarded as achievable by EWEA. In fact, EWEA predicts for the EU to have 80 GW installed capacity, including 3.5 GW offshore by 2010 and set target of 180GW installed capacity, including 35GW offshore by 2020, which is equivalent to approximately 5% of total power supply in 2020. As of the end of 2007, Europe had over 57GW of installed wind power capacity, most of it in wind farms. At the end of 2008, there was over 1000MW of installed offshore wind capacity, most of it in Europe [4].

Wind farms as mentioned, are locally concentrated groups of wind turbines that are electrically and commercially tied together. First concept of offshore wind turbines developed in Germany in 1930s by Hermann Honnef. In Europe, the first actual offshore wind turbine was installed in Sweden in 1991 and the first real offshore wind farm was constructed in 1992 in shallow water off the coast of Denmark near the town of Vindeby, still operative [2]. Since then, offshore wind turbines have been installed in the Netherlands, the United Kingdom, Sweden, Ireland, Germany. In recent years, the number of wind turbines installed in Europe has increased tremendously. Many of these wind turbines are in coastal areas. The primary impetus for offshore farms has been the lack of available land with a good wind resource for wind turbines, particularly in northern Europe. The first offshore wind farm installations would be set at Mediterranean Sea in 2017, near the coastline of France. Figure 1.1 presents installed and under construction European’s offshore wind farms. All mentioned North European countries are marked. [1; 4]
European Environment Agency (EEA) estimated offshore potential of European countries (Figure 1.2). The estimation was done according to available offshore area per km² for wind energy farms within national jurisdictions. The highest potential is observed for United Kingdom, Sweden, Norway and Finland [1]. All mentioned countries have already have installed offshore wind farms. From the estimation done by EEA it is easily seen that Italy, one of targeted country for this thesis, has tremendous opportunities in offshore locations but many difficulties to be overcome.
1.1.3 Planned offshore wind farms in Mediterranean

First Mediterranean offshore wind farm would be placed near the coastline of France. This wind farm would consist of slightly different wind turbines than the most commercial ones. Those turbines would be an innovative vertical-axis floating turbines designed for waters depth up to 200m [6]. Before the start of this project, the test site was chosen and the two versions of the 2MW vertical-axis wind turbine prototype are tested for 18 months. This test started in 2014 and it is positioned of about 5km offshore nearby St. Louis Port. Chosen prototype supposes to establish best operating wind turbine for Mistral winds. The final product, the first offshore wind farm in the Mediterranean Sea should be installed in 2018. The completed farm would consist of 13 wind turbines with the final capacity of 26MW and it would be placed 22km offshore in the Gulf of Lion [6; 7]. Similar project were active in the waters of Italy and Spain for Mediterranean Sea. The Italian project was situated in the Southern Adriatic Sea, near the coastline of Brindisi on the east coast of the Italian peninsula. This project started just with a prototype in 2008 and up to now there were not installed wind farm. The wind turbine prototype was a tension leg-floating platform with 80kW wind turbine. The offshore wind farm supposed to be sited 10km from the nearest coastline, in order to minimize the visual impact of the facility. The project under consideration supposed to provide a total nominal power of 315-525MW, with a single turbine power of 3-5MW and a hub height of 100m. Wind farm suppose to occupy an area 67,2km² with a project lifetime of 29 years [7].

An overview of planned offshore project in the Mediterranean [8] counts many projects by the end of 2020 and those project are divided into various parts of the basin. This overview places 5 wind farms in Mediterranean waters of Spain and various project suited for Italian waters projected by 2020. The Italian waters are divided into Mediterranean Sea, which counts 7 projects and in Adriatic Sea, counting 15 projects where one of locations is the Gulf of Trieste. This offshore wind project should have installed capacity of 30MW and be placed 24km off shore. This overview counts 2 projects in Malta, three project in Croatia and one in Albania. For Greece it is planned the installation of almost fifty offshore wind farms by 2020.

1.2 Physical characteristic of wind and wind energy

In the next section the main characteristics of wind and estimation of wind power are presented. The region of interest for this thesis together with its prevailing wind patterns, are introduced here. In the discussion of the general characteristics of the wind resources it is important to present quickly nature of the wind along its general characteristics and then to move to estimate of the wind resource potential.
1.2.1 General characteristics of the wind resource

Global winds are caused by pressure difference across the earth’s surface caused by unequal heating and cooling across the earth’s surface. Air always tries to flow from higher to lower pressure until the pressures are equalized. The greater the difference in pressure between two points, the higher the values of wind will be.

The amount of solar radiation absorbed at the earth’s surface is greater at the equator than at the poles. The variation in incoming energy sets up convective cells in the lower layers of the atmosphere (the troposphere). Uneven absorption of solar energy force air to rises at the equator and sinks at the poles. The circulation of the atmosphere that results from uneven heating is generally influenced by the effect of the rotation of the earth (Coriolis effect). In addition, seasonal variations in the distribution of solar energy give rise to variations in the circulation. At the same time, there are forces that strive to mix the different temperature and pressure air masses distributed across the earth’s surface. In addition to the pressure gradient and gravitational force, inertia of the air, the earth’s rotation and friction with the earth’s surface (resulting in turbulence), affect the atmospheric winds. The influence of each of these forces on atmospheric wind systems differs depending on the scale of motion considered. The influence of each of these forces on atmospheric wind system differs depending on the scale of motion considered [10]. The predominately winds blow in the horizontal plane, responding to horizontal pressure gradients. Worldwide wind circulation involves large-scale wind patterns covering the entire planet. The large-scale of wind patterns includes doldrums, jet stream, polar easterlies, trade winds, and westerly winds. It should be noted that this model is an oversimplification because it does not reflect the effect that land masses have on the wind distribution.

1.2.2 Mechanics of wind motion

The simplest model for the mechanics of the atmosphere’s wind motion is approximated with geostrophic wind. Geostrophic wind has two main features, as no friction and blows parallel to isobars. Winds in nature are good approximations to geostrophic winds especially in upper atmosphere. In this simplified model for atmosphere’s wind motion only four atmospheric forces can be considered. These include pressure forces, the Coriolis force caused by the rotation of the earth, inertial forces due to large-scale circular motion, and frictional force at the earth’s surface.

The pressure force on the air $F_p$, is given by:

\[ F_p = -\frac{1}{\rho} \frac{\partial p}{\partial n} \]  
(1.1)

Where \( \rho \) is the density of the air and \( n \) is the direction normal to lines of constant pressure. Also, \( \frac{\partial p}{\partial n} \) is defined as the pressure gradient normal to the lines of isobars. The Coriolis force, \( F_c \), an apparent force caused by measurements with respect to a rotating reference frame (the earth), is expressed as:

\[ F_c = fU \]  
(1.2)

where \( U \) is the wind speed and \( f \) is the Coriolis parameter \( f = 2\omega \sin \phi \). \( \phi \) represents the latitude and \( \omega \) the angular rotation of the earth. Thus, the magnitude of the Coriolis force depends on wind speed and latitude. The direction of the Coriolis force is perpendicular to the direction of motion of the air. The resultant of Coriolis and pressure gradient, called the geostrophic wind, tends to be parallel to isobars (Figure 1.3) [10].

![Figure 1.3. Geostrophic wind, balance between forces.](image)

The magnitude of the geostrophic wind, \( U_g \), is a function of the balance of forces and is given by:

\[ U_g = -\frac{1}{f\rho} \frac{\partial p}{\partial n} \]  
(1.3)

Described general circulation flow pattern represents a model for a smooth spherical surface. Actually, the earth’s surface varies considerably with vast ocean and land surfaces. These different surfaces affect the flow of air due to variations in pressure fields, the absorption of solar radiation, and the amount of moisture available. For example, the sea acts as a large sink for energy. Therefore movement of air over the sea is affected by ocean circulations, which influence on its turn changes in the direction of persistent global winds.

In the atmosphere, motion takes place at all spatial and temporal scales simultaneously. Figure 1.4 summarized the time and space variations of atmospheric motion. In describing atmospheric processes, therefore atmospheric motion as applied to the wind energy, temporal
and spatial variations of wind speed needs to be considered together.

Figure 1.4. Time and space scales of atmospheric motion.

Time variations of wind speed are divided into the inter-annual, annual, diurnal and short-term (gust and turbulence) categories. An understanding wind patterns, and local effects, is important for the evaluation of potential wind energy sites.

The inter-annual variations in wind speed have a large effect on long-term wind turbine production. The ability to estimate the inter-annual variability at a given site is almost as important as estimating the long-term mean wind at a site. Significant variations in seasonal or monthly averaged winds are common over most of the world. Information of variations over the season in mean wind speed is significantly important for locating wind farms. Large wind variations also occur on a daily time series. This type of wind variation is due to differential heating of the earth’s surface during the daily radiation cycle. A typical diurnal variation is an increase in wind speed during the day with the wind speed lowest during the hours from midnight to sunrise. The largest diurnal changes generally occur in spring and summer, and the smallest in winter. Furthermore, the diurnal variation in wind speed may vary with location and altitude above sea level. There may be significant year-to-year differences in diurnal behavior, even at fairly windy locations. Short-term wind speed variations are also present which include turbulence and gust. Those variations are usually expressed as mean variations over time intervals of ten minutes or less (see also Chapter 2).

After introducing the mechanism of wind, we can introduce the estimation of available energy from the wind. The productivity of a wind farm at a specific location could be estimated assuming that wind resources are measured and available. However, in most wind energy applications, information of reliable wind speed data for the location of interest is not available.
Introducing a suitable methodology to respond to this issue is one of a scope for this thesis.

1.2.3 Physical characteristic of wind resources

As previously defined, wind speed is the rate at which air flows past a point above an earth’s surface. Wind contains kinetic energy that can be converted to mechanical power using wind turbine. The kinetic energy of air-flow provides the motive force that turns the wind turbine blades that provide the mechanical energy to power the generator in the wind turbine. Energy of air-flow is referred to as the wind power density. Wind power is a measure of the energy available in the wind [11].

We want to express wind energy density in terms of available wind speed. If we consider the standard wind turbine with a rotor disc of area $A$, we can determine the mass flow of air, $m$, through a rotor disc with $dm/dt$.

From the continuity equation of fluid mechanics, the mass flow rate is a function of air density, $\rho$, and air velocity, $U$, and is given by:

$$\frac{dm}{dt} = \rho AU$$ \hspace{1cm} (1.4)

The kinetic energy per unit time, or power, of the flow is given by:

$$P = \frac{1}{2} \frac{dm}{dt} U^2 = \frac{1}{2} \rho AU^3$$ \hspace{1cm} (1.5)

The wind power per unit area, $E$ or wind power density is:

$$E = \frac{P}{A} = \frac{1}{2} \rho U^3$$ \hspace{1cm} (1.6)

where the wind power density is proportional to the density of the air. For standard conditions (sea-level, 15°C) the density of air for standard atmosphere at sea level is $1.225\,\text{kg/m}^3$.

The maximum available power (Equation 1.6) would be obtained if theoretically wind
turbine could capture all wind coming to the swept rotor area without any losses. A. Betz, a German physicist, in 1919 calculated that no wind turbine could convert more than 59.3% of the kinetic energy of the wind into mechanical energy turning a rotor. This is known as the Betz limit, and it is the theoretical maximum coefficient of power for any turbine. Within this approximation wind turbine would be able to reduce upwind speed to the zero at the swept rotor area [11].

The wind velocity is an important parameter and significantly influences the power per unit area available from the wind. Where the annual averages of wind speed are known, corresponding maps of average wind power density could be computed. In order to develop a classification between certain regions we could consider the annual average wind speed and develop maps that show average wind power density. These are sample qualitative magnitude evaluations of the wind resource for annual wind speeds:

\[
\frac{P}{A} < 100 \frac{W}{m^2} - \text{low}
\]

\[
\frac{P}{A} \approx 400 \frac{W}{m^2} - \text{good}
\]

\[
\frac{P}{A} > 700 \frac{W}{m^2} - \text{great.}
\]

Based on wind resource data and on estimate of the real efficiency of actual wind turbines, numerous investigators have estimated the wind power potential of regions of the earth and on the entire earth itself and consequently potential estimation of wind energy [11].

The actual power production potential of a wind turbine must take into account the fluid mechanics of the flow passing through a power-producing rotor, and the aerodynamics and efficiency of the rotor/generator combination. This issue would be processed in more details in the Chapter 3. The maximum power-producing potential that can be theoretically realized from the kinetic energy contained in the wind is about 60% of the available power [11; 2].

In practice, the relationship between the power output of a wind turbine and wind speed does not follow a linear relationship (Equation 1.6). Wind turbines can produce energy only in response to the wind immediately available and within a range prescribed by with wind power curve. Figure 1.6 presents the most common wind power curve. The production of a wind turbine is related to three key points characterized with wind speed; cut-in speed, i.e. which is the minimum wind speed at which the machine will deliver useful power, the rated wind speed, the wind speed at which the maximum power output of the electrical generator is reached, and the cut-out speed that is the maximum wind speed at which the turbine is allowed to deliver power, limited by engineering design and safety constraints.
When the annual distribution of wind speed and the characteristic of a given turbine are known, the annual energy production can be estimated for a specific site. One of main difficulties for wind farm management consists in the lack of available observational data according to which future projections could be made, especially offshore. The overall potential for wind depends heavily on accurately mapping the wind resource. Efforts to improve the mapping of the global wind resource are ongoing and further work will be required to refine estimates of the wind resource. There is currently a lack of data especially for offshore regions.

1.2.4 Introduction for region of interest

Mediterranean Sea is lying between latitudes 30° and 46° N and longitudes 5°50’W and 36°E. It is west-east extent from the Strait of Gibraltar between Spain and Morocco to the shores of the Gulf of Iskenderun on the southwestern coast of Turkey. The western extremity of Mediterranean Sea is connected with the Atlantic Ocean by the narrow and shallow channel of the Strait of Gibraltar. The Suez Channel links the Mediterranean with the Red Sea and the Bosporus to the Black Sea. It stretches over 4000km from Gibraltar on the west and Israel to the east. The Sea is divided into different parts by islands and peninsulas. The Aegean is the sea between Greece and Turkey, the Adriatic Sea lies between Italy and Balkan Peninsula and the Tyrrenian Sea is between Italy and its western islands. Mediterranean Sea is almost completely surrounded by land with of three continents, Europe, Asia and Africa.

This semi-enclosed basin creates and interesting climatic system by itself. Complex orography and land-sea interaction areas are suitable for formation of persistent local winds occur on a various time scales. Weather conditions are affected by conditions generated either in the Atlantic Ocean or in northwestern Europe. Figure 1.5 illustrates prevailing local wind patterns for the basin. Presented local winds occur on a various time scale, from several days up
Buoys offer instantaneous and continuous observations of wind speed over vast Mediterranean Sea. Observations provided in this way are available only in situ and often are not positioned at locations to be affective for wind farm planning and management. In Chapter 2 we will analyze numerical simulations of wind speed for the present climate by regional climate models over the Mediterranean Sea in order to fill the gaps in observational fields.

Chapter 3 move a one step forward and introduce the Large Eddy Simulation for simulating wind turbine.
Chapter 2

As mentioned in previous Chapter the possibility to increase the skill in predicting wind speed at specific locations are crucial for wind industry. Regional Climate Models could provide relevant information about present climate and future projections for specific regions. The information provided with regional climate models is relevant in making a decision in long terms investments.

In this Chapter we report the possible information obtained by using regional climate models. Targeted information is elaborated to support preplanning in locating the suitable sub-areas for offshore wind farms.

The Chapter 2 is organized as follows. In following section, we present a general overview of Regional Climate Models. Then, we describe satellite data used to validate the Regional Climate Models runs. The analysis here follows the mentioned theory in Chapter 1 for estimating the potential wind resources. The evaluation of the regional simulations and the wind resource potential assessment will be presented in details. Finally, a short summary and concluding remarks considering regional analysis is reported.

2.1 What are Regional Climate Models?

Climate is defined as an average state of the atmosphere for a given time and for a specified geographical region. Climate models simulate the climate system with the set of equations based on physical laws, including the conservations of momentum, mass and energy. Figure 2.1 shows the interaction of climate system. The mathematical equations are translated into a code where they are solved numerically within a three dimensional grid containing a climate-related physical information about a particular location. That numerical tool is called Regional Climate Model (RCM) and is fundamental in climate research.
The driving data for RCMs is derived from Global Circulation Models (GCM) and/or analysis of observations and include various forcing and parametrizations of complex physical processes occurring at smaller scales. RCMs can provide relatively high resolution (up to 50 to 10 km or less) and multi-decadal simulations and are capable of describing climate feedback mechanism acting at the regional scale.

RCMs are used in a wide variety of applications including processes studies, data assimilation and analysis, attribution, historical and paleoclimate simulation, seasonal to inter-annual climate prediction, present climate simulations and future climate projections. Information provided by RCMs is useful in evaluating intra daily variability and extremes, together with long-term climate variability.

Targeted information is essential for projecting the impacts of climate change and application required in impact analysis. To validate whether or not climate models provide accurate information about the climate system outputs from model simulations are compared to observational data to assess their skill in reproducing observed climatological features [13].

2.2 Introduction in regional analysis

Constant growth in renewable energy demand [14] requires larger wind farms and installed in locations where high, reliable and predictable wind resources are available. As mentioned in previous Chapter, the wind resources are even more abundant and of better quality over the sea.
Vast offshore areas could be potential locations for harvesting the wind and converting it to electrical power [14; 15]. Planning and selecting optimal locations for wind farms needs expertise from many fields of engineering to economics, environmental impact, meteorology and climatology. In order to map the best offshore locations to extract wind energy, near-surface wind speed observations and model output can be used. There are two possible observations of surface winds: direct and indirect observations.

Over vast offshore areas instantaneous daily wind observations are provided only in situ. Buoys, mainly positioned along the coast, offer direct observations of instantaneous daily near-surface wind speed. However, buoys are not always suited at the exact locations where wind farm exist or is in further plan to be made. Observations provided in this way are too sparse and are not always continuous to be effective for wind planning and management. The collected wind observations provided in this way are too sparse and are not always continuous to be effective for wind farm planning and management. Many researchers have noted that a major barrier to wind industry deployment in many regions of the world is a lack of reliable and detailed wind resource data [16; 17].

By contrast, scatterometer satellite, which is a remote sensing technique, is able to monitor the near-surface wind speed indirectly over vast area such as a global sea [18]. Monitoring done by transmitting microwave pulses from the scatterometer, down to Earth’s surface, measure the strength of the backscatter signal to the instrument. Differences in transmitted and received signal are related to the roughness of the ocean waves, and can be used to determine the surface wind speed over ocean surface. The first mission in wind observations started in late 1970s and was pursed with various shifts among the satellite generation, providing the daily/twice daily information of 10 m wind speed above the global ocean surface [15]. Even so, in evaluating these available wind data it is important to realize the data’s limitations.

Despite progresses in observations, the need of homogenous and consistent wind data sets covering both continental and vast areas over the global seas requires the use of numerical models. Despite their relatively low resolution, RCMs have been used to simulate wind speeds over specific domains and the potential of wind energy [19; 20]. RCMs are able to produce long, multi-decadal time series of high frequency outputs, both in time and space, as compared to satellite data. RCMs are also used to produce projections of future climate [13] and the consequences on wind energy [21; 22]. However some studies have highlighted some deficiencies of RCM in representing surface winds. e.g. Vautard et al. (2014) found that overall the Weather Research and Forecast (WRF) model overestimate near-surface wind speeds over land [23]. Although the impact for wind energy could not be estimated due to the lack of turbine-height long-term wind measurements, this suggests that some limitations have to be taken into account when estimating the wind potential from models.
So far, various studies have investigated wind speed representation and related energy resources through RCMs simulations. Pryor et al. (2012) assessed the effect of RCM resolution on wind speed and gusts for the 20 years run period (1987-2008) over Northern Europe [16]. They concluded that simulations with higher spatial resolution generate higher extreme values. Rasmussen et al. (2011) studied climate change impact on wind energy over California [24]. They evaluated future trends in average surface wind speed and frequency using three global climate models (GCMs) to force two RCMs. This study highlighted that several RCMs and GCMs forcing have to be used in order to better evaluate uncertainties for future projections. Pryor and Barthelmie (2011) investigated the future projections of mean wind energy over the North America using three RCMs [19]. Hueging et al. (2013) studied impacts of climate change on wind energy over Europe considering ensemble projections from two climate models for the end of twenty first century [21]. They projected increases in wind power over northern and central Europe and decrease over the Mediterranean basin. Tobin et al. (2014) showed weak, but robust, signals in European wind energy production to be expected under SRES A1B scenario over the 21st century [22]. The mentioned study of Tobin et al. (2014) counts also as one part in this thesis research and it would be given additional attention in Section 2.5 at the end of this Chapter.

The Mediterranean region has a high density of a population, which implies a high demand of energy. The need and increase in low-carbon energy production places the Mediterranean Sea as good potential choice in wind harvesting. Despite this, very few studies have attempted to estimate the wind energy potential over the Mediterranean Sea. Lavagnini et al. (2006) used a very high-resolution limited area model to produce a short time series of wind data over the Mediterranean basin. They produced maps of mean wind speed with the aim to illustrate the areas suitable for wind energy application in the basin [20].

2.3 Data and methods

2.3.1 Observational data

The reference observational dataset used here to validate the RCM simulations over the Mediterranean Sea is derived from the Sea Winds instruments on board the NASA’s Quik Scatterometer (QuikSCAT) satellite. This dataset is available from the 19th July 1999 up to the end of 2009. The satellite measured surface stress twice daily (approximately at 0600 and 1800 LST), with a swath of 1800km providing 90% daily coverage of Earth’s oceans. The Kriging interpolation was applied to obtain measurements and to produce the daily mean wind speed at 10m above the global sea surface with a spatial resolution of 0.5x0.5 degrees on a regular grid. The cloud coverage in the atmosphere could affect the satellite observations. QuikSCAT
product provides this information (rain flag) [18]. The rain flag information was used to identify and select reliable data used in our analysis.

The QuikSCAT products are one of the widely used dataset to validate the present wind climate simulation. Over the Mediterranean basin the QuikSCAT product have been assessed and verified using buoy data [25]. The QuikSCAT products have also been used to produce maps of wind energy density over the global seas [26].

2.4 Description of RCMs simulations

In this thesis, four simulations are used produced from two RCMs, each in different configurations. The first two simulations were performed by ENEA UTMEA-CLIM laboratory, while IPSL-LSCE performed the other two simulations.

ENEA UTMEA-CLIM laboratory performed two simulations of present climate using a PROTHEUS model [27]. The PROTHEUS system integrates model where RegCM3 model for the atmospheric component and MITgcm for the oceanic component, coupled through OASIS3 coupler.

First simulation we consider is the run of RegCM3 stand-alone atmospheric model as uncoupled run of the PROTHEUS model. RegCM3 is a 3-dimensional, primitive equations, sigma-coordinate, hydrostatic stand-alone atmospheric RCM [28]. The model is configured onto a standard uniform horizontal grid with spacing of 30km on a Lambert conformal projection. It has 16 sigma vertical levels. The estimation of river discharge is accomplished with a river routing scheme (interactive river scheme, IRIS). Sea surface temperature is taken from global re-analysis and interpolated to the model grid used as initial and boundary conditions during the simulation. The model uses CCM3 as radiative transfer scheme (Kiehl et al. 1996), with specific GHG concentrations, Grell’s cumulus convective scheme (1993) and the planetary boundary layer scheme from Holtslag et al. (1990) [28] are used.

Second simulation from ENEA UTMEA-CLIM laboratory is produced using coupled PROTHEUS model. MITgcm (MIT General Circulation Model) has been developed at MIT in 1997. It is a primitive equation, non-hydrostatic implicit free-surface model. The topography in the model is represented by the intersecting boundary method. The ocean model for Mediterranean region was set as non-uniform spatial resolution 1/8° x 1/8°, (the finest spacing is achieved in the northern part of the domain). It has 42 unevenly spaced vertical levels [27]. The interpolation of the coupled field is accomplished onto RegCM3 grid. MITgcm model supplies fields of the sea surface temperature to RegCM3, while RegCM3 computes the wind stress and heat fluxes for the ocean model [27].
Both simulations cover the time frame from 1989 – 2010 over the region of the European region including the Mediterranean. The ERA-Interim [29] reanalysis has been used to force the models out of the Mediterranean domain with no inner nudging. The outputs are saved with the 6-hourly frequency. Daily mean wind speed is estimated by taking twice per day 12-hourly spaced simulated values in order to be comparable with satellite data.

The IPSL-LSCE laboratory performed two simulations with the Weather Research and Forecasting Model (WRF, version 3.3.1 [30]) for the present climate over the European basin. These runs are part of the EURO-CORDEX modeling project [23; 31; 32; 33]. The model domain and resolution thus follow the project specifications. The simulations cover the time period 1989 – 2008. The runs were carried out at two spatial resolutions; a high resolution run with a spatial grid of about 12x12km (WRF11) and a low resolution run with a spatial grid of about 50x50km (WRF44). Both runs use the same physical parametrization. The simulations use 32 vertical levels with a terrain-following hydrostatic pressure vertical coordinate. RRTMG established by Iacono et al. (2008) is applied as radiation scheme, Grell and Devenyi (2002) as convective scheme, Hong et al. (2004) as microphysics scheme. WRF model uses Noah Ek et al. (2003) as a land-surface scheme and YSU (Hong et al. 2006) as boundary layer scheme [34].

The ERA-Interim reanalysis are used to force the model domain boundaries, and no inner nudging is performed except in the 4 outer rows and columns of grid cells. The outputs were provided at the daily resolution. Unlike for QuikSCAT dataset and ENEA simulations, daily mean wind speed is calculated considering all daily time steps in the model run.

The analysis in this Chapter is conducted over the overlapping period between the satellite observational product and simulated fields (2000 - 2008). We used in-situ buoy observations in the Gulf of Lion to further assess the ability of RCMs to simulate surface winds. The region of interest is the Mediterranean basin, considering the variable of wind speed variable at 10 m above the surface.

### 2.4.1 Wind Resource Atlas

In order to assess the wind resource and feasibility of wind farm projections, here we present a possible approach in estimating and sorting wind energy potential over the region.

Wind turbines harvest kinetic energy of wind and convert it to electrical power. Harvested energy is proportional to the cube of wind speed and is defined as a wind energy density (Equation 1.6.) introduced in Chapter 1, Section 1.2.4.

Important for wind industry one of the most relevant issues is the description of wind speeds. The distribution of occurrence of wind speeds could be described by the probability density function, \( p(u) \). A various distribution functions have been used to fit the best distribution of wind speed. Many scientists agree that the general uses for describing the distribution of
wind speeds are Weibull and Rayleigh probability density functions [35; 36; 37]. Distribution of both function is skewed, i.e. it is not symmetrical. Weibull distribution is two-parameter family of distributions, characterized with shape and scale parameters. Mentioned parameters are function of mean wind speed and standard deviation. The Rayleigh distribution is a special case of Weibull function and holds for the simplest wind speed probability distribution. The wind resource with Rayleigh distribution is represented requiring only knowledge of the mean wind speed, $\bar{U}$. The Rayleigh probability density function is given by:

$$p(u) = \frac{u}{\bar{U}} \frac{1}{\sqrt{2\pi}} \exp \left[-\frac{u^2}{2\bar{U}^2}\right]$$

(2.1)

where $u$ is instantaneous wind speed [38; 39].

We want to classify the estimated wind energy density and to provide a ranking of different areas in the region of interest. The information of region classification would be used as an initial indicator in ranking and mapping the potential sub-regions in wind farming. As mentioned before, QuikSCAT dataset provides the information of daily and not the instantaneous wind speed and we cannot be used a straight forward in Equation (1.6).

C.C.Iff et al. (1977) proposed a technique for classification of wind resources using just the information of annual wind speed [40]. The hypothesis used in the mentioned study have been established by Justus et al. (1976) who considered that mean wind speed with values higher than 4.5m.s$^{-1}$ tends to have Rayleigh distribution function [36].

Based on these assumptions, the cube of annual mean wind speed can be estimated using following equation.

$$U^3 = \bar{u}^3 \left(\frac{4}{\pi}\right)^\frac{3}{2} \frac{3}{2} \Gamma\left(\frac{3}{2}\right) \approx 1.91 \bar{u}^3$$

(2.2)

Where $u$ is considered here as daily wind speed and the bar indicates the average over a specified time period (the annual time scale). Then the average amount of available potential power is:

$$E \cong 0.955\rho u^3 \quad [W.m^{-2}]$$

(2.3)

By using Equation (2.3) we are able to rank the potential wind resources and produce a wind atlas. Classification is expressed in terms of power classes. Each class represents a range of mean wind power density estimated from wind speed at 10 m above the ground (Table 2.1) [41]. Classification in this way was introduced by U.S. Department of Energy in 2006 for the Wind Energy Resource Atlas and is widely used. The scale ranges from class 1 to class 7, ranking the poorest and the highest wind resource respectively. Commercial wind farms have to be installed in areas characterized with classes higher than 3 to be considered as profitable [41].
Table 2.1. Classes of Wind power density at heights of 10m [41].

2.5 Results

2.5.1 Analysis of Observational data

Figure 2.2 presents maps of seasonal average QuikSCAT surface wind speed.

Figure 2.2. Fields of average QuikSCAT surface wind speed for seasons March April May (MAM), June, July, August (JJA), September, October, November (SON) and December, January, February (DJF); 2000-2008. Max/min observed values of seasonal fields are reported in the upper left corner [42].
The prevailing winds in the basin occur near the coast of France and Spain (Mistral winds) and over the Greek archipelago (Etesian winds). Stronger winds are observed in winter, especially for the sub-region of the Gulf of Lion and of the Sea of Crete. Light winds occur in summer with minimal values in the central part of the basin. Spring and autumn winds show similar pattern, although, lighter winds occur in the North Adriatic and Tyrrhenian Sea during spring. The annual average (Figure 2.4, the upper map) is closer to spring and autumn, with observed maximum of 8.7 and minimum 4.5 m/s values.

In order to evaluate the intra-seasonal variability of the wind field, we first remove the mean annual cycle from the data. The mean annual cycle has been estimated from time period of 9 years by calculating a 365 pentad (moving window) for each grid points. The standard deviation was then calculated (Figure 2.3). In the performed analysis part of variability can include the intra-seasonal variability. The intra-seasonal variability would be explained in more details in Section 2.4.

![Figure 2.3](image)

Figure 2.3. Standard deviation fields of QuikSCAT observations with removed seasonal cycle [42].

From Figure 2.3, we find maxima of wind speed standard deviation over the Gulf of Lion in all four seasons. Low values of standard deviation occur especially in summer, while high values are observed in winter. While mean fields for spring and autumn are quite similar,
standard deviation maps show large differences. Those differences are evident over the Gulf of Lion and over the southeast part of the basin. In autumn the gradient of the spatial pattern of standard deviation over the Gulf of Lion is higher than in spring. In autumn lower values of standard deviations are observed over the southeast part of the basin than in spring.

2.5.2 Comparison between observed and simulated fields

The simulated fields of wind speed were re-gridded to the grid of satellite observations for further analyses. We calculated annual average of wind speed for the QuikSCAT observations and the simulated fields. The comparison among modeled and observed annual mean wind fields has been performed (Figure 2.4).

![Figure 2.4](image)

**Figure 2.4.** Annual mean values of QuikSCAT data on (the map on the top); the mean annual differences: RegCM3 compared with QuikSCAT (upper left map), PROTHEUS compared with QuikSCAT (upper right map), WRF11 compared with QuikSCAT (lower left map) and WRF44 compared with QuikSCAT (lower right map) [42].
The maximum overestimations of models are within the value of 1.9m.s\(^{-1}\) achieved by RegCM3 model while the highest maximum value for underestimation is found with the WRF11 model with the value of -3.45m.s\(^{-1}\). WRF44 performs better than other models with regards to the annual average. All the models overestimate the annual mean wind speed over the sub-regions of the Alboran and Tyrrhenian Sea. RegCM3 and PROTHEUS models underestimate the values of annual average wind speed for the sub-region the Gulf of Lion. At the annual scale, wind speeds in the central part of the basin are slightly overestimated by all the models. The Greek archipelago and the eastern part of the basin is characterized with the local overestimation for the RegCM3, the PROTHEUS and the WRF44, while WRF11 experiences more uniform overestimation with respect to the annual average values of wind speed for the QuikSCAT data.

We further analyze the degree of similarity of simulated wind speed and wind energy density estimations from RCMs with satellite observations.

The degree of similarity of simulated wind speed and wind energy density estimations from RCMs with observations is further analyzed by comparing the simulated wind data against in-situ buoy observations in the Gulf of Lion. We compared the simulations with only one buoy observations because the availability of buoy data is limited in the Mediterranean basin. The comparison method follows the same procedure as in Ruti et al. (2008) regarding the collocation procedure and the comparison time period (years 2002 to 2005). A statistical comparison has been preformed using scatter diagrams (Figure 2.5). RegCM3 and the PROTHEUS are rather positively correlated with in-situ observations, while both WRF models are spread along the diagonal. All models slightly underestimate low winds (<5m.s\(^{-1}\)) and overestimate strong winds (>10m.s\(^{-1}\)). In this case, RegCM3 and PROTHEUS simulate quite well off-shore winds, while two WRF models reveal some problems.
Figure 2.5. Scatterplot of daily mean wind speed comparing in-situ buoy observations and model outputs in the Gulf of Lion [ms⁻¹]. Upper left figure refers to buoy vs RegCM3, upper right to buoy vs PROTHEUS model, lower left to buoy vs WRF11 and lower right to buoy vs WRF44 model.

While on preformed analysis we achieved in-situ comparisons with buoy data, over the entire basin the degree of similarity would be assessed for wind speed and wind energy density with satellite observations. Taylor diagram [43] offers a concise graphical summary explaining how closely simulations correspond to observations on a single diagram. The correspondence is evaluated in terms of correlations, standard deviations and root-mean-square difference. These diagrams are especially useful in evaluating multiple aspects of complex models or in gauging the relative skill of many different models.
Above cited statistics of observed and simulated spatial fields were performed using only the sea-points over the Mediterranean basin for the wind speed and estimated wind energy density. The annual values are presented in the Taylor diagram (Figure 2.5). Letters were assigned to each considered model and observations. The position of each letter appearing on the plot quantifies how closely that model’s simulated annual mean wind speed matches observations. Full statistic is shown in a table 2.2 for wind and 2.3 for wind energy density field of entire time period and of four seasons.

The models show similar correlation for the fields of 10m wind and wind energy density. For annual values, better correlation for all models is achieved for wind energy density. The highest correlation with the observational field was achieved with the WRF44 model for both fields of wind speed and wind energy density. Slightly better correlation with the value of 0.704 with WRF44 model is achieved for wind speed. All simulated datasets are characterized by a similar root-mean-square difference for both fields. WRF44 achieves the closest measure of root-mean-square difference. Spatial variability is well represented by all models. RegCM3 simulates the standard deviation of wind field better than other models while the WRF11 simulates better the wind energy density.
### 2.5.3 Estimation of Wind Resources

Spatial pattern of annual wind energy for the present climate is first estimated and classified (Figure 2.6). Classification of wind resources provides general information within a large area and should be used in pre-selection in wind farm sites. Considering just information of spatial classification of wind resources cannot provide enough information for the detailed examination of candidate sites for wind development.

---

**Table 2.2.** Wind speed statistic for entire period and four seasons.

<table>
<thead>
<tr>
<th>Wind speed [m.s(^{-1})]</th>
<th>ALL</th>
<th>MAM</th>
<th>JJA</th>
<th>SON</th>
<th>DJF</th>
</tr>
</thead>
<tbody>
<tr>
<td>mean</td>
<td>σ</td>
<td>rmsd</td>
<td>corr</td>
<td>mean</td>
<td>σ</td>
</tr>
<tr>
<td>WRF44</td>
<td>6.310</td>
<td>0.330</td>
<td>0.000</td>
<td>1.000</td>
<td>6.379</td>
</tr>
<tr>
<td>RegCM3</td>
<td>6.386</td>
<td>0.361</td>
<td>0.475</td>
<td>0.655</td>
<td>6.497</td>
</tr>
<tr>
<td>PRTH</td>
<td>6.323</td>
<td>0.302</td>
<td>0.468</td>
<td>0.664</td>
<td>6.492</td>
</tr>
<tr>
<td>WRF11</td>
<td>6.509</td>
<td>0.464</td>
<td>0.474</td>
<td>0.691</td>
<td>6.571</td>
</tr>
<tr>
<td>WRF44</td>
<td>6.486</td>
<td>0.387</td>
<td>0.433</td>
<td>0.704</td>
<td>6.620</td>
</tr>
</tbody>
</table>

**Table 2.3.** Statistic for wind energy density for entire period and four seasons.

<table>
<thead>
<tr>
<th>Wind Energy Density [W.m(^{-2})]</th>
<th>ALL</th>
<th>MAM</th>
<th>JJA</th>
<th>SON</th>
<th>DJF</th>
</tr>
</thead>
<tbody>
<tr>
<td>mean</td>
<td>σ</td>
<td>rmsd</td>
<td>corr</td>
<td>mean</td>
<td>σ</td>
</tr>
<tr>
<td>QN</td>
<td>329.5</td>
<td>84.6</td>
<td>0.000</td>
<td>1.000</td>
<td>335.1</td>
</tr>
<tr>
<td>RegCM3</td>
<td>322.8</td>
<td>83.7</td>
<td>0.485</td>
<td>0.649</td>
<td>322.5</td>
</tr>
<tr>
<td>PRTH</td>
<td>322.1</td>
<td>81.4</td>
<td>0.550</td>
<td>0.618</td>
<td>322.7</td>
</tr>
<tr>
<td>WRF11</td>
<td>345.9</td>
<td>98.7</td>
<td>0.422</td>
<td>0.674</td>
<td>346.3</td>
</tr>
<tr>
<td>WRF44</td>
<td>320.9</td>
<td>87.3</td>
<td>0.4155</td>
<td>0.671</td>
<td>322.4</td>
</tr>
</tbody>
</table>

Spring and summer mean wind values are better represented with RegCM3 while for the same seasons the PROTHEUS model achieves better the mean for wind energy density. Autumn mean is better represented with WRF44, while winter mean values are better represented with WRF11 considering both fields. Spring, autumn and winter values of standard deviation are represented better with WRF11 for both fields, except for winter wind statistic where RegCM3 takes advantages. Summer standard deviation is better achieved with WRF44. In spring root-mean-square distance of wind field is better represented with WRF44 while for wind energy field with WRF11. The same statistic for summer is better achieved with WRF44 for both fields, while for autumn with WRF11. In winter root-mean-square difference for wind field simulated with RegCM3 reaches achievement better with QuikSCAT data while for field of wind energy density it is achieved with WRF11 model. While WRF11 have the highest correlation for spring and winter, summer statistic is better achieved with WRF44 model.

Despite the differences among physical characteristics of models, they do show quite similar behaviors.
Figure 2.7. Energy potential atlas of Mediterranean basin estimated from 10m wind fields expressed into power classes; 1, ‘poor’, 2, ‘marginal’, wind energy density = 100-150 Wm\(^{-2}\); 3, ‘fair’ 150-200 Wm\(^{-2}\); 4, ‘good’ 200-250 Wm\(^{-2}\); 5, ‘excellent’, 250-300 Wm\(^{-2}\); 6, ‘outstanding’, 300-400 Wm\(^{-2}\); 7, ‘superb’ 400 Wm\(^{-2}\) and higher. Upper map holds for QuikSCAT satellite observations, upper-left map for the RegCM3, upper-right for the PROTHEUS model, lower-left map holds for the WRF model with high resolution and lower-right map holds for the WRF low resolution. In upper left frame of the maps there are maximum and minimum observed values of wind energy in [W.m\(^{-2}\)] [42].

Similarities among the models occur. RegCM3 and PROTHEUS models are in reasonable agreement for the representation of wind power classes. Differences are observed over the Tyrrhenian Sea, the Adriatic Sea and over the eastern part of the basin near the Turkish coast, where RegCM3 estimates wind power class slightly higher than PROTHEUS model does. WRF models differences in terms of wind classes are marked. Over the eastern part of the basin, the WRF11 model estimates wind power classes higher than the WRF44 model does. Compared with wind power atlas obtained from QuikSCAT observations, RCMs overestimates wind classes in the sub-regions of the Alboran Sea (the Strait of Gibraltar), the Tyrrhenian Sea and the central part of the basin.

Figure 2.7 quantifies the overall spatial occurrence of wind classes considering only points over the Mediterranean Sea for all four simulations compared with the QuikSCAT data.
are considered. Histogram shows that models estimate in similar manner the small values of wind power classes while QuikSCAT data do not represent these classes as expected. WRF model features a tendency in underestimating the intermediate classes with an overestimation of higher classes, while RegCM3 and the PROTHEUS exhibit the opposite behavior especially for the higher classes.

![Figure 2.8. The histogram of occurrence in wind power classes for the region of Mediterranean [42].](image)

There is a strong relationship between wind energy production and wind speed (Equation 2.2). However, the turbines do not produce electrical power for all wind conditions. A range of wind speeds when turbines are in a functional range to produce electrical power is established with wind power curve, introduced in Chapter 1, section 1.2.4, Figure 1.6. Those limits are based according to a mechanical characteristics and safety reasons for the turbine’s blades [36].

Now, it would be considered only days when the wind turbine is inside the functional range. This functional range varies from turbine to turbine but a theoretical values are set to be 3.5m/s for a cut-in speed and 25m/s for a cut-out wind speed. Herein it would be considered those values for turbine’s functional range.

In Figure 2.9 it is reported maps of the mean numbers of days per year within the turbine’s functional range for QuikSCAT data and the four simulations.
Figure 2.9. Mean annual average number of days in a range between cut-in and cut-off speed estimations for QS - upper panel, the RegCM3 - upper left, the PROTHEUS - upper right, the WRF model at higher resolution - lower left and the WRF at lower resolution – lower right. In upper left frame of the maps there are maximum and minimum observed values of current maps [42].

The RegCM3 and the PROTHEUS models estimate a similar mean number of days inside the functional range. By contrast, some discrepancies between both WRF simulations are highlighted. The WRF at higher resolution better represents the functional range pattern of wind speed when compared to satellite observations with respect to the lower resolution simulation over the main part of the basin. More in general, RCMs overestimate the annual number of days inside the turbine’s functional range over the Tyrrhenian Sea, except WRF44. Underestimation of the values over the southwestern part of the basin is found for all models. Models are not able to simulate the variety of wind speed range as it is observed with QuikSCAT satellite. They simulated more days within the range 3.5 – 14 m/s than observations (figure not shown).

The only model being able to reproduce the extreme winds (> 25 m/s) is the WRF at higher resolution. The information of extreme wind condition is important since the wind turbines have to be shut down for safety reasons. Extreme winds as identified by QuikSCAT satellite and reproduced by WRF at higher resolution are observed over the North Adriatic and
over the Gulf of Lion. Both satellite observation and the WRF at higher resolution reproduce extreme winds over North Adriatic and over the Gulf of Lion (figure not presented).

The spatial occurrence of mean number of days per year between cut-in and cut-out wind speed have been quantified using only points over the Mediterranean Sea on a histogram for QuikSCAT data and simulation (Figure 2.10).

![Figure 2.10. The histogram of number of days inside the turbine’s functional range for all the Mediterranean grid points [42].](image)

Models predict values in occurrence of lower bins for mean number of days per year between cut-in and cut-out wind speed while for QuikSCAT data those values are not present. All models reasonably estimate median values of days per year inside the functional range. High values are quite similarly estimated with the RegCM3 and the PROTHEUS models where overestimation is found in the 290-315 days range of the bins following with the underestimation inside the highest values ranges of the bins. Deviations are present inside the higher ranges of bins for the number of days inside the functional range for WRF model at both resolutions. The WRF44 model experiences the opposite pattern with respect to what showed by RegCM3 and the PROTHEUS models. The WRF11 is the best model in estimating wind functional range frequency for the medium-to-high bins.
2.6 Variability of wind speed

One of the most critical features of wind energy is the variability of the wind. Wind speed is by nature intermittent on daily, intra-seasonal and annual time scale. Information about the intra-seasonal variability and annual cycle of wind speed would give us an important tool in prediction and fluctuations of wind energy production [17].

The ability to estimate the temporal variability at a given site is almost as important as in estimating the long-term mean wind at a site. It is valuable to be able to understand and than to predict or forecast variability of the wind resource. This information would be valuable for wind farm operator to be able to predict outputs of wind turbine into a grid. As the process in mapping the best location for wind farm proceeds, knowledge of the wind resource in finer and finer detail is required.

It is generally determined that for long-term variability in atmosphere, reaching a reliable average annual wind speed at a given location could take at least five years [1]. The best choice would be to have 30 years of observational data. Nevertheless, shorter data records can be useful. Here, it was used 9 years of data to map the temporal variability.

2.6.1 Intra-seasonal variability

We removed seasonal cycle from the data and then applied fast Fourier transform to convert the data from time to frequency domain for every point over the basin. Frequency domain was used to select and distinguish between different events over the basin, which occur at specific ranges of frequencies. A scheme in translating time to frequency domain is presented on a Figure 2.13.

![Figure 2.11. Scheme of time to frequency domain transformation.](image)
Frequency domain separates the events from high frequency holding for events occurring on daily to weekly frequencies, up to middle frequencies holding for monthly events, to low frequencies holding for seasonal and intra-annual events. Then, frequency domain was utilized to select only the frequencies of interest, creating a filter. Only the data with selected frequencies were converted back to time domain and the maps of standard deviation for satellite observation and models were created.

Three different time windows were selected; first we considered just events with high frequencies (1 week – 1 month) (Figure 2.12), intermediate (1-6 months) (Figure 2.13) and finally events with low frequencies occurrence (6 months up to 9 years) (Figure 2.14) of the data. High values on maps indicate a significant change in wind speed over the corresponding time period.

A high frequencies events, considering time occurrence from two until 30 days of the data were selected. This type of wind speed variations is due to differential heating of the earth’s surface during the daily radiation cycle. Anti-cyclones whose usually occur in Mediterranean basin with periods of about 4 days are recognized inside selected high frequencies events. Dominated high frequency events over the basin are observed over the Strait of Gibraltar, north Balearic, west Ligurian, entire Aegean Sea and Sea of Crete. Persistent events with time occurrence from two days until 30 days are present over Strait of Gibraltar, Greek archipelago and with strong occurrence over Balearic Sea. All models underestimate
events of high frequencies over the Balearic Sea, sub-region placed for Mistral winds and overestimate events over Strait of Gibraltar.

In the second time window analyzed we consider intermediate frequencies corresponding to intra-seasonal variability. Variability from one until six months are present for west part of the basin observed over Balearic Sea and over Greek archipelago with strong variability. Models estimate in good manner intermediate frequency where underestimation is present over eastern part of the basin and less evident maxima over the Balearic Sea and stronger events over Aegean Sea.

We observe that over the sub-region the Gulf of Lion with strong signals of Mistral winds are present from daily to inter-seasonal scales. All models tend to underestimate daily to inter-seasonal variability, where WRF11 shows a good agreement for the representation of variability.

![Figure 2.13. Maps of variance for inter-seasonal frequencies (1-6 months).](image)

Finally, inter-annual variability (6 months up to 9 years) is reported in Figure 2.14. Prevailed inter-annual patterns are present over Balearic and Ligurian Sea and southern of Italy. While models capture well low and middle frequency events, they differ in estimation of the low frequency events. All models estimate well low frequency events over Ligurian Sea, while variations in the sub-regions south of Italy presented for satellite observations are shifted over Greece archipelago. RegCM3 and PROTHEUS models strongly overestimate low frequency
events over Adriatic Sea compared with satellite observations. Models are not able to capture the signal of intra-annual variability present in the observations.

All models are able to reproduce and capture variability of the data over the region. The WRF at higher resolution reproduce better high and middle frequencies events than other models.

2.6.2 Representation of annual cycle

We decompose considered time series of wind fields using five days moving average for all sea-points. The mean annual cycle was determined and a Probability Density Function (PDF) of anomalies from the annual cycle was calculated for the entire region (Figure 2.15).
Figure 2.15. Annual cycle of 10m winds speed (left) and non-parametric (Kernel) distribution of anomalies of the annual cycle (right) for the Mediterranean Sea. The results are specified with corresponding colors where black is assigned for satellite observations, RegCM3 is purple, PROTHEUS is blue, WRF at higher resolution is green and WRF at lower resolution is red.

The annual cycle for entire basin is captured. Strongest winds occur in winter reaching maxima in January with the highest values of 8.7m/s, while calm winds occur in summer with lowest values of 5.4m/s in June. Models do represent well annual cycle with the same phases of oscillations. Those phases were better described in analysis considered the selection of events occurring at different frequencies. PDF of anomalies is well estimated by all models, except WRF44 (noticed with red color).

Considering the outcomes reported in previous Sections, we replicate the analysis of seasonal cycle for selected sub-regions as the most appealing for wind energy application in the Mediterranean Sea; the Strait of Gibraltar close to Spanish coast, the Gulf of Lion, the sub-area west of Sardinia, South of Sicily, the central part of the basin, the Greek archipelago and the west part of the Turkish coast. The most interested regions could be the coastal line of France and Spain and the Greek archipelago. However, extreme winds, which appear in the coastal area, could be dangerous for the mechanical properties of a wind turbine.

2.6.3 Sub-regional analysis

From entire region we would select three potential sub-regions to locate wind farms. Considering the overall presented analysis we selected the Gulf of Lion (within the box of 3.25°E - 7.25°E in latitude and 41.75°N - 43.75°N in longitude), the Sea of Crete (22.75°E - 26.75°E latitude and 35.75°N - 37.75°N longitude) and the North Adriatic (11.25° - 15.75°E latitude and 43.75° - 45.75°N longitude). Those sub-regions are fairly self-selected if we consider only the maps of intra-seasonal variability of wind. In the Gulf of Lion the strong wind
signal of Mistral winds is present from daily to inter-seasonal scales. In the Sea of Crete the signal of prevailing winds is occurred from daily to inter-seasonal scales (Etesian winds). And finally, in the North Adriatic the signal of prevailing winds is occurred from daily to seasonal scales. Figure 2.16 presents time series and PDF of anomalies of selected sub-regions.

Figure 2.16. Annual cycle of 10m wind speeds (left) and non-parametric (Kernel) distribution of anomalies of the annual cycle (right) for the regions: upper the Gulf of Lion, middle the Sea of Crete, lowest the North Adriatic. The results are specified with corresponding colors where black is assigned for satellite observations, RegCM3 is purple, PROTHEUS is blue, WRF at higher resolution is green and WRF at lower resolution is red [42].

A well-captured annual cycle for all three sub-regions is observed. Strong winds are present in period from November to March while calm winds occur in the period from May to September. Slightly different behavior is observed for the sub-region of the Sea of Crete where the values of wind reach the maxima in February, while the minimum values in observations occur during the period from May to June.

In the sub-region of Gulf of Lion we observe the strongest winds respect to the other two sub-regions. QuikSCAT data has a mean value of 7.73m/s and amplitude considered
between max and min values of the annual cycle with a value of 6.01 m/s. From Figure 2.16 we observe that models reproduce quite well the annual cycle and intra-seasonal variability. However all models underestimate the amplitude of annual cycle, even if the mean value is closely reproduced. Concerning the PDF of anomalies models tend to overestimate the bulk while they underestimate the tail of the distribution.

In the Sea of Crete signal of prevailing winds are present from daily to inter-seasonal scales (Etesian winds). Daily variability over the sub-region is captured well in all models. Inter-seasonal variability is overestimated with all models, except for WRF11. Overestimation in inter-seasonal events for RegCM3, PROTHEUS and WRF44 models are followed by slightly overestimation in inter-annual cycle. In Figure 2.16 (middle figure) it is presented the annual cycle for the sub-region of Sea of Crete. WRF11 reproduces better the amplitude of the annual cycle and the mean values than the other models do. Moreover, the WRF11 is reproducing well the minima in summer and overall behavior for the last months of the year. A relevant overestimation of inter-seasonal variability for RegCM3, PROTHEUS and WRF44 (not shown here) could be motivated by an abrupt summer jump of the annual cycle. Finally, for the Sea of Crete, the bulk of PDF anomalies underestimate by all models.

In the North Adriatic sub-region the signal of prevailing winds are mostly from daily to seasonal scales. WRF11 provides the best representation of daily and inter-seasonal variabilities over this sub-region. RegCM3 and PROTHEUS overestimate daily variability with a feasible estimation of inter-seasonal variabilities, while WRF44 underestimate the variability at daily and inter-seasonal time scale. Inter-annual variability is overestimated in RegCM3 and PROTHEUS models, while WRF44 model exhibits a good agreement with QuikSCAT observations. Over the North Adriatic sub-region we observe the lowest mean value in the QuikSCAT wind annual cycle (5.63 m/s) and the lowest amplitude (3.59 m/s) in relation with the other two sub-regions. The RegCM3 and the PROTHEUS models overestimate the amplitude of the wind annual cycle, while both WRF models underestimate it. WRF11 overestimate the most PDF of anomalies while it is reproduced well by the other.

2.7 Future projections of wind energy

Despite the fact that the Earth’s wind power potential is worldwide and large, global warming could alter the intensity and pattern of near-surface winds which ‘fuel’ wind turbines, through in particular large-scale circulation changes. Since the wind power potential scales with the cube of the wind speed, small changes in wind speeds may induce significant changes in harvested energy. Given the current and expected development of wind energy, the climate change impacts on this energy need to be addressed.
To investigate the changes of wind energy over the European and Mediterranean domain, it was applied a simplified wind power generation model to an ensemble of 15 regional climate projections achieved from 10 RCMs downscaling six GCMs under the SRES A1B emission scenario from the ENSEMBLES project. These simulations have now been widely studied and under for climate change and impact studies. Since the uncertainties related to model formulation can be large, multi-model investigation are generally required to assess the (un)certainty level of the findings [22].

The simulated surface wind speeds were first evaluated against observations. The reference observational datasets used here are the QuikSCAT satellite data over ocean and the in-situ measurements from the ISD-Lite database over land. Almost all simulations overestimate 10 m wind speed overt the continental areas (about 20% on average by the model ensemble mean) and underestimate it over the sea (about -10%).

In order to access the future projections, biases were removed in the historical and scenario wind speed distribution using the Cumulative Distribution Distribution-transform (CDF-t) method developed by Michelangelie et al. (2009) [44]. The transformation is calibrated against the QuikSCAT and ISD-Lite derived with climatological distribution computed as described above.

Future changes in the wind power potential are assessed considering a characteristic of a 3MW wind power turbine and a hub height of 90m. It is assumed that no substantial future changes will occur in the technology used to harvest winds in the next decades. Under this assumption, which approach allows the assessment of future changes in the local potential for wind power production at any place in Europe, in a view of future deployment of onshore and offshore wind farms. To test the sensitivity of results to a change in turbine fleet, a 2020 fleet scenario designed by Vautard et al. (2014) following the Energy and Climate policies was also considered here. Future changes are computed as the difference between the mean values obtained for the 1971-2000 present periods and the 2031-2060 and 2071-2100 future periods.
On average over the model ensemble, future mid-century changes in surface wind speed relative to the means over the recent past period are found to be weak and not robust at the annual scale over a large part of Europe. Several regions however exhibit robust changes. Near-surface wind speeds are projected to slightly decrease over most of the Mediterranean region while they are expected to increase by a few percent over the Bosporus and the Strait of Gibraltar. It was found a tendency toward a decrease of the wind power potential over Mediterranean areas.

Therefore, climate change should neither undermine nor favor wind energy development in Europe and over Mediterranean. Regarding the perceptibility of the climate change signal indicates that the future changes are rather spall compared to the inter-annual variability of present wind power production.
2.8 Comparison between RegCM3 and the PROTHEUS models

The efficiency of regional climate models in estimating wind energy was presented. In next Chapter, we would like to carry out the research in model efficiency in estimation the wind energy from regional to local scale. According to presented analysis we observed that two models, RegCM3 and the PROTHEUS, are in reasonable agreement with QuikSCAT data in comparison with annual mean values of wind speed and maps of wind resources. In order to determine which of this model pair would be exposed and roughly compared in following analysis with local-scale model we present an additional analysis considering those two models.

We requested seasonal comparisons of wind power classes for RegCM3 and the PROTHEUS models. The seasonal occurrence of wind power classes are plotted on a histogram (Figure 2.18) and compared with the QuikSCAT data.

![Figure 2.18. The histograms of occurrence in wind power classes for four seasons for the RegCM3 and the PROTHEUS model.](image)

We observe that RegCM3 and the PROTHEUS models estimate in similar manner occurrence in wind classes and minor deviations are present. Strongest deviation between two models is present in autumn. In spring, models underestimate middle classes while strongly overestimate class 6. Summer is characterized with strong occurrence in lower wind power classes while models do not represent well those values. Summer middle and high wind classes are occurred well for both models. In autumn occurrences in wind classes are characterized with
overestimation in lower and middle classes while underestimation is present for higher classes. In winter, models do represent low classes while for QuikSCAT data, those classes are not observed.

As for previous analysis, also here, seasonal spatial occurrence of mean number of days when a wind turbine is inside the functional range for the RegCM3 and the PROTHEUS models are presented. We created bins with width of 7 days and we separated data in which they occur within the same bin size. Both models for all seasons estimate in a good manner lower bin widths with evident small values. Link between histograms of spring and autumn are occurred. Lower bin values are experiencing the same behavior with extremely small values while for present underestimation in spring is followed with overestimation in autumn and vice versa. In summer, all events in all bins are present, where both models estimate it in good manner. In winter, models estimate days inside the functional range much more in bin ranges of 65 until 79 days per season while for QuikSCAT data, there are present stronger occurrence in higher bin range.

Seasonal analysis with the RegCM3 and the PROTHEUS models was performed in locating the most reliable source and constant production in wind energy. We inquired a rough threshold with 85% occurrence in mean number of days whose are inside the turbine’s functional range. This threshold was applied to the basin and it is used to produce seasonal maps (Figure 2.20).
Figure 2.20. Seasonal maps presenting locations with values higher than 85% in mean number of days inside the turbine’s functional range. Titles in upper part of the maps refer to (a) MAM is for spring, (b) JJA summer, (c) SON autumn and (d) DJF for winter season.

In spring, overestimation in spatial fields with applied threshold of models are present in Gulf of Gibraltar, Balearic Sea, Tyrrenhian Sea and central part of the basin. Summer in the basin is characterized with calm winds, which reflect in mapping just an area over the Greek archipelago with positive outcome. In autumn, models slightly overestimate mean numbers of days inside the functional range in west part of the basin, and deviations are present in the central part of the basin. In winter, overestimation in mean number per days are present in Tyrrenhian Sea, while underestimations are present in central part of the basin with respect to
QuikSCAT data. Considering this threshold, the East part of the Mediterranean have the best positive outcome in harvesting the wind for all four seasons.

If the threshold is required to be higher then 85% of days whose are inside the turbine’s functional range then the potential sub-regions reduces significantly. Only sub-regions in the Gulf of Lyon, west of Sicily close to African coastline and Greek archipelago are mapped as potentially good areas for harvesting the wind, considering the four seasons.

Even thought, in presented additional analysis both deviations between two models are minor. The PROTHEUS model achieves slightly closest estimations than RegCM3 with QuikSCAT data. This is warranted with the physical complexity of the PROTHEUS model whose is the only one coupled atmosphere-ocean model presented in these analysis.

2.9 Summary and conclusion

In this Chapter we have analyzed regional climate simulations of wind speed and wind energy density over the Mediterranean basin using the following models: RegCM3; PROTHEUS; high-resolution WRF model (WRF11); low-resolution WRF (WRF44). Model outputs have been compared against QuikSCAT satellite observations. The results have been carried out to verify the reliability of model simulations in the re-production of the most relevant features of present climate. The information was elaborated with the aim to find some potential sub-regions for installation of wind farms over the vast region of Mediterranean Sea.

A wind resource atlas including indications of variability, such as maps of average number of days whose conditions lie within the wind turbine’s functional range have been presented over the basin. Following this approach, we have selected sub-regions as potential for wind energy applications in the Mediterranean Sea: the Strait of Gibraltar close to Spanish coast, the Gulf of Lion, the sub-area west of Sardinia, South of Sicily, the central part of the basin, the Greece archipelago and the west part of the Turkish coast.

The focus on the models’s skill in reproducing the wind over the basin was evaluated for the three sub-regions. Two of three sub-regions (the Gulf of Lion, the Sea of Crete) are selected as the most appealing potential areas for wind farms while the other one sub-region (the North Adriatic) could be taken into account to better analyze the RCM behavior over the complex orography. The models’s skill has been evaluated considering the annual cycle and the intra-seasonal variability expressed in term of the probability density function of anomalies. The analysis demonstrates the skills of the models in reproducing the annual cycle and intra-seasonal variability of the wind speed over the sub-regions. Analysis of selecting events with different frequencies over the basin was performed to better analyze diurnal, inter-seasonal and intra-annual variability for the selected sub-regions. All models are able to reproduce and
capture events at different time scale over the region. Inter-seasonal variability observed inside
the annual cycle could be cause of a cyclonic activity over the basin.

As regards model skill, the highest resolution model (WRF11) is able to represent
better the complexity of terrain orography and the variability and extremes of winds. In
particular this model is able to reproduce extreme winds observed in the Gulf of Lion and the
Northern Adriatic (wind speed higher than 25m/s). The relevance of model resolution in re-
producing the extremes is in agreement with other studies investigating the effect of horizontal
resolution such as S.C. Pryor et al. (2012) [16]. Besides the high capability to reproduce the
extreme values at high resolution, WRF model is also able to reproduce the mean number of
days per year inside the functional range as in QuikSCAT data.

It was presented a methodological framework for providing future changes in the
potential of wind power production. Overall, multi-model analysis indicates that, under
Scenario A1B, future changes in wind power potential are found to decrease over the
Mediterranean region, with the exception of the Aegean Sea where it is exhibits a robust
increase. Such results are consistent with previous studies: the decrease in wind power potential
over the Mediterranean Sea with the exception of the Aegean Sea was also highlighted in
Hueging et al. (2012) [21].

The account of climate change in energy scenario is justified. The climate change
indirect effect on wind energy infrastructures through its impact on extreme events can also be
important for wind power industry.

The analysis carried out in the present Chapter contributes to fill the gaps of sparse
observational data, by using regional climate models. Until now, QuikSCAT dataset and RCMs
simulations have not been taken into account for wind energy applications over the
Mediterranean region. Studies like this constitute a step forward in maintaining and enhancing
the usage of regional numerical models in the wind industry applications.

The first part of this thesis, reported in this Chapter, was done at the research centre
ENEA Casaccia at technical unit UTMEA. The efficiency of regional climate models in
estimating wind energy was presented. Next, we would like to carry on the research in model
efficiency of estimation the wind energy onto local scale. In Chapter 3 we would consider local-
scale model (Large-Eddy Simulation) and implement parameterization of wind turbine inside
the local-scale numerical model in order to simulate real case wind farm.

According to already assess differences between satellite observations and RCMs in
Chapter 2, in Chapter 3 we would focus on reporting the dynamical downscaling of only one
RCM with LES model. Followed procedure in Chapter 3 differs than reported in Chapter 2
where the dynamical downscaling of QuikSCAT observations would be expected. In order to be
consistent with performed analysis in Chapter 2, we would assess the efficiency of RCM model in simulating wind speed on selected location for offshore wind farm with QuikSCAT observations. Then, we would compare the ‘real’ wind farm power production obtained by LES with estimation of potential wind power by regional climate model. With this procedure, we would like to inspect the numerical added value and justify the usage of regional and local scale models in application of wind energy.

As for regional climate model we would use the PROTHEUS model (implemented in UTMEA facilities), while for local-scale model we would use LES-AIR in-house model of University of Trieste. The PROTHEUS model was chosen according to the analysis in Section 2.9 and assessed correspondence in scatter plot diagram with the in-situ buoy observations in the sub-region the Gulf of Lion. Second part of this thesis, considering the usage of LES-AIR model and implementation of wind turbine parameterization, was done at University of Trieste.
Chapter 3

Wind energy is becoming more and more important in reaching the EU goal in utilization of renewable energy sources. Wind turbines and wind farms are becoming larger in need to satisfy the growing market of wind energy. The new wind farms are planned and will be installed all around Mediterranean Sea.

Since there is a constant growth in wind energy application the need in simulation of wind turbine has become important. It is important to acquire a deep understanding in harvesting the wind, and then use gained information for future projections. In the framework of numerical simulations for wind turbine applications there is a broad variety of models whose are alternatively employed depending in the specific goal. There is still a lot to learn and to understand behind the physical characteristics of wind energy.

The goal of this Chapter is to present a local scale numerical framework designed in simulating the cases important to wind industry. The ability of considered numerical framework in simulating real case wind farm would be tested on a theoretical wind farm. Theoretical offshore wind farm would be positioned according to gained information of Regional Climate Models reported in Chapter 2. In order to assess the local characteristics of wind farm, dynamical downscaling of one RCM would be performed with Large-Eddy Simulation (LES) for one test location. Then, LES adaptation and approach for wind energy application would be performed. Wind turbine inside the numerical LES code would be parameterized by simple actuator disc model. The highly idealized offshore wind farm would be designed from theoretical values. The actual wind power estimations obtained from the theoretical offshore wind farm would be then finally presented and compared with potential wind power estimations performed by RCM.

The Chapter 3 is organized as follows. In following section, we present a computational fluid dynamic and its application to wind energy with an overview large-eddy simulation framework for wind turbine parameterization. Then, we describe LES-WIND model used to create atmospheric conditions above the sea surface and the model’s implementation to the wind turbine. The numerical setup and experiments are illustrated. First a single turbine, then theoretical wind farm is discussed in details. The evaluation of wind power from idealized wind farm is presented. Finally, a short summary and concluding remarks considering the large-eddy simulation for wind turbine application is reported.
3.1. Computational fluid dynamic and wind energy application

One of many characteristics of a wind turbine, which still needs to be understand in details is the downstream wake created as a byproduct in extracting energy from the flow. If wind turbines are arranged in an array, as in most of wind farms, wakes from upwind turbines may interact with downwind turbines. This introduced wake effects that decrease of power production.

In the last two decades, numerical modeling of wind turbine wakes using computational fluid dynamics (CDF) has become increasingly popular [45]. Numerical simulations can complement experimental studies and lead to a better understanding of the flow through wind turbines and wind farms. With an improved understanding of this type of flow, wind farm developers could plan better performing wind farms to maximize the wind energy production. In addition, numerical simulations can also provide valuable quantitative insight into the potential impacts of wind farms on local meteorology.

It is agreed that only deeper understanding of the nature of turbulence and the mathematical properties of the Navier-Stokes equations will lead to controlled improved turbulence models for use in wind turbine aerodynamic applications [46]. The numerical models for wind turbine applications require two important parameterizations: a turbulence model simulating the atmospheric flows and parameterizations for the turbine-induced forces.

Turbulence is an unresolved problem of classical physic. Because of the non-linearity of the fluid motion, there are no analytical solutions, except for simplified cases. Navier-Stokes equations have a great impact on the study of fluid motion. At the moment the only way to face Navier-Stokes equations is numerically. Direct numerical solution of those equations (DNS) offers understanding of physics behind the equations but the solutions are not feasible for most of the practical flows. Problem with DNS is that all scales of motion are directly solved and that simulations are limited just to low Reynolds number flows. Due to high Reynolds number flows in the atmospheric boundary layer, direct numerical simulation of Navier-Stokes equations is not suitable choice.

For many applications of fluid motion it can be sufficient to supply the effects of the turbulent motion just with the mean flow. Models that consider these physical assumptions are often calibrated through experiments. Reynolds Averaged Navier-Stokes equation (RANS) is one of mentioned approach where the flow is resolved for the mean flow and all the scales of motion are parameterized. It is an extremely cost-saving procedure with respect to DNS. The problem with using RANS in wind farm optimization is that turbulence models are usually over-dissipative in the wake region.

On the other hand, large-eddy simulation (LES) provides the greater level of fidelity by preserving both temporal and spatial fluctuations on the flow to computational grid. LES is
much more computationally intensive than RANS. In LES the turbulence is treated explicitly, except for turbulent eddies smaller than the grid size of the CFD simulation, whose are then modeled as ‘sub-grid eddy viscosity’ [47]. It should be mentioned that RANS and LES represent alternate approaches to the problem of modeling turbulence, and that each model has its own benefits and shortcomings. Both RANS and LES methodologies have been used in solving the problem of turbulence in atmospheric boundary layer.

The parameterizations of turbine-induced forces embedded in atmospheric models come in many different varieties of complexity in scales of resolution with regard to different involvement. The simplest turbine’s model is a drag element model which extracts momentum and inject turbulence over a few simulation grid points of a computational domain. The next level of complexity is a blade element momentum (BEM) models that calculate blade forces and the wake influence using a momentum balance. The forces in this model are then distributed around a disk and the influence of axial and rotational momentum is then propagated into the wake. Recent calculations of multiple turbine interactions have used actuator-line methods, where the blades are treated as airfoils distributed along rotating lines. More about parameterization of wind turbine especially used in this thesis would be given in Section 3.4.

As with wind models, researchers have used RANS, unsteady RANS, detached eddy simulations (DES) (a hybrid model between RANS and LES), and LES to simulate the flow around wind turbines and wind farms [45]. Common to both atmospheric flows and wake modeling the model developer has to design a model evaluation strategy which provides us that the model is correctly verified and provides an accurate representation of the real case from the perspective of the intended uses of the model (validation).

The current state of knowledge concerning atmospheric boundary layer with the large wind farms and the interface among the wind turbines inside the wind farm is not complete. Scientists all around the world use a computational fluid dynamics to simulate and understand interactions of atmospheric boundary layer with large wind farms and the flow inside the wind farms both in energy and atmospheric community.

### 3.1.1 Outline of wind turbine parameterization done in LES framework

Wake modeling of wind turbines originated in the 1980’s with work by Ainslie (1988). He developed algebraic model, which is still widely used for wind farm layout. This model is based on simple momentum and fluid dynamic similarity theories or simplified solutions of the Navier-Stokes equations. The model was simple and computationally fast, suggested the use to provide reliable estimates of wake deficits for designing wind farms [48]. Finally, Ainslie
produced a single wake model with the aim to calculate the wake velocity field behind a wind turbine taking into account of all relevant meteorological influences. The results of this model were compared with available experimental data, showing good agreement with both wind tunnel studies and filed data. The drawback of the model is the lack of many required physical processes needed to predict wind turbine wake, which, at the end resulted in unpredicted wake losses by 10% observed in many operational wind farms [45].

Various authors have performed simulations of small groups of turbines with LES. For example, Porté-Angel et al. (2014) created neutrally stable wind flow directly from LES used then to compare different wind turbine parameterizations (actuator disc versus actuator line) implemented within the LES wind field. They simulated a section with five turbines of an operational farm and compared profiles with field data [49].

Another prominent work is of Calaf et al. (2010), whose LES simulation of wind farm was aimed at understanding interaction between atmosphere and wind farm [50]. They systematically studied a fully developed flow inside wind turbine array where wind turbines are modeled using the classical drag disc concept. The performed simulations were done for various wind-turbine arrangements, turbine loading factors, and surface roughness values. The results were used to quantify the vertical transport of momentum and kinetic energy across the boundary layer. Calaf et al. did not carry out comparison with field data because their performed simulation of idealized wind farm was focused in interaction of wind farm and the atmosphere.

Few scientist performed simulations of wind farm and compared their results with the measurements gained from wind tunnel. Porté-Angel et al. (2010) focused in development and validation of a LES framework for wind energy application [51]. They parameterized turbine-induced lift and drag forces using two type of models: an actuator disk model (ADM) that distributes the force loafing on the rotor disc, and an actuator line model (ALM) that distributes the forces on lines that follow the position on the blades. They compared simulation results with wind-tunnel measurements collected with hot-wire and cold-wire anemometry in the wake of a miniature 3-blade wind turbine at the St.Anthony Falls Laboratory. They concluded that in general the characteristics of the wind turbine wakes simulated with the proposed LES framework are in good agreement with the measurements.

Wu and Porté-Angel (2014) used LES coupled with a wind-turbine model to investigate the characteristics of a wind-turbine wake in a neutral turbulent boundary layer. The parameterization of turbine-induced forces was made using two models: the standard actuator-disc model (ADM-NR) with no rotation, and the actuator-disk model with rotation (ADM-R). They compared simulation results with the wind-tunnel measurements obtained with the same methodology from the St.Anthony Falls Laboratory. The characteristics of their simulated results are in good agreement with the measurements in the far-wake region. The ADM-R yields improved prediction compared with the ADM-NR in the near-wake region. They showed
that the Lagrangian scale-dependent dynamic SGS model is able to account, without any tuning, for the effects of local shear and flow anisotropy on the distribution of the SGS model coefficient [52].

Tossas and Leonardi (2012) compared the performance of actuator disc and actuator line model in producing wind turbine wakes and the wake-turbine interaction between multiple turbines with LES. They examine influence of models performance onto different grid resolutions and they concluded as the grid is coarsened, the predicted power as final result from wind turbine parameterization decreases. When the width of the Gaussian body force projection function for turbine-induced force is increased, the predicted power increased. They concluded that the actuator disk and actuator line models produce similar wake profiles and predict power within 1% of one another when subject to uniform inflow. Then they show that the actuator line model is able to capture flow structures near the blades, but in far wake actuator line and actuator disc model look similar. Finally they show that actuator models for wind turbine aerodynamics are viable alternative for wake simulations [53].

Performance of large-eddy simulations in wind turbine applications are compared with measurements of existing wind farms by several authors. Creech et al. (2014) presented a simulation of an offshore wind farm using LES and a torque-controlled actuator disc model for turbine parameterization. They provided a detailed description of the turbine model that simulates the interaction between the wind, the turbine rotors, and the turbine generators by calculating the forces on the rotor, the body forces on the air, and instantaneous power output. They investigated the case where a row of turbines is fully aligned with the wind and at specific angles to the wind. The results from the simulations were compared to observations of the operational wind farm (Lillgrund wind farm) to provide a firm quantitative validation of their methodology. Cross-validations considered comparison with simulated and measured power outputs from the individual turbines. They achieved good agreement between the model results and actual wind farm measurements [54].

Steinfeld et al. (2010) applied LES to the analysis of flow conditions at Germany’s first offshore wind farm Alpha Ventus. The actuator-disk as well as actuator-line method were implemented in highly-parallelized LES model PALM. They compared results between the new LES model and previously published LES results and measurements of the wake behind a single wind turbine, respectively. Their results are in qualitative agreement with the measurements, although they aligned shortcomings of the actuator disc approach. Simulated results indicated that an increase of the turbulent exchange with areas of higher momentum leads to a faster recovery. This fact is attributed to the created wake of first and second row of turbines in the considered farm [55].

Jimenez et al. (2007) developed CDF code based on a LES approach. The turbine was simulated by concentrated drag forces, and is placed in an environment with turbulence
anisotropy properties similar to the ones in the real atmosphere. They performed analytical corrections of simulations according to experimental measurements. Finally, they suggested that LES is a potentially useful tool in the investigation of detailed wake flow [56].

Churchfield et al. (2012) presented simulated results of Lillgrund wind farm with LES using OpenFOAM CDF toolbox. They created a turbulent inflow performing an atmospheric boundary layer precursor simulation, where turbines are modeled using a rotating, variable-speed actuator line representation. The performed simulation of time-averaged production of the turbines agrees well with field observations except with the sixth turbine and beyond in each wind-aligned. The power production by each of those turbines is over-predicted by 25-40%. Their simulation show the significant 60-70% decrease in the performance of the turbines behind the front row in the simulated wind farm that has a spacing of 4.3 rotor diameters in streamwise direction. They concluded that simulated farm efficiency is well predicted even they agree that more work is needed to determine the best method of body force onto the CDF grid [57].

Ivanell et al. (2010) performed LES to simulate the Horns Rev offshore wind farm. Their aim was to achieve a better understanding of the wake interaction inside the farm. Actuator-disk method was used for parameterizing the wind turbine. Their study showed that the applied method captures the main production variation within the wind farm and that level of production correlate well with measurements [58].

While a single wind turbine would only affect the atmosphere locally in the form of a wake decaying over the length scale of around ten rotor diameters, the cumulative effect of a whole wind farm on the atmosphere is much greater [54]. Roy et al. (2004) found that the effect on vertical mixing through the turbulence generation by the rotor blades can lead to warming near the surface in stable atmospheric conditions, and cooling in unstable conditions [54]. Porté-Angel et al. (2014) found the effect of large wind farms is not only noticeable behind the turbine array but also above, as the wind farm induces its own developing boundary layer with significant upwelling observed at heights well above the turbines [49]. Brostrom (2008) reported that flows, in the upper layer of the oceans are affected by large offshore wind farms [60]. Large wind farms on both the horizontal and vertical scales have increased to the point that their presence can be expected to affect weather and climate and should therefore be included in climate models through a suitable parameterization [61]; [62].

All mentioned authors showed that a large-eddy simulation has high potential in simulating the turbine wake and as a final goal application in wind industry. LES is a research tool and the best practice how to adopt LES to flows inside the wind farms have yet to be fully established.
3.2 LES-WIND framework for wind energy application

In this section the mathematical and numerical models that are the basis of the LES-WIND solver are described. LES-WIND is a modified LES-AIR code already used and tested for the atmospheric research [64] with an option to switch on/off the parameterization of wind turbines. First the governing equations together with used approximations are presented explaining the mathematical and then numerical models. The numerical simulations would be initiated with already tested LES application for atmospheric research in order to simulate the atmospheric field over the sea. The performed simulation of wind field would be considered as initial field for further application. Then, the parameterization of the turbine-induced force will be presented and the new adaption and implementation to the LES-WIND code to wind industry would be presented. The procedure would be followed, in order to simulate first a single wind turbine then the theoretical offshore wind park.

3.3 Description of the LES-WIND model

The LES-WIND is a numerical model, which solves Navier-Stokes equations under Boussinesq approximation. It is in-house numerical model, developed by the research group of University of Trieste, Department of Engineering and Architecture. The numerical code is written in Fortran 77/90 and it works on parallel environment using the Message Passing Interface (MPI) routines. Origin of LES-WIND, the LES-AIR is verified for the various applications. The code is mainly developed to study pollutant dispersion and flow dynamic in coastal area with very high definition [63].

3.3.1 The governing equations for LES-WIND

The flows in the atmosphere are characterized by the presence of turbulence. A turbulent flow field is chaotic and dissipative, and is characterized by the presence of large amount of vorticity and strong mixing. Turbulent flows are still an unresolved problem of classical physics. With some approximation (regarding the air flow as incompressible and density variations considered with Boussinesq approximation) the atmospheric flow can be described by Navier-Stokes equations treated with numerical solvers.

In order to numerically solve the incompressible Navier-Stokes equations, large-eddy simulation technique applies a low-pass filter to the equations. Within this technique equations
are spatially filtered into a resolved (large eddies) and sub-grid part (small eddies). The large scales are resolved directly while the scales that lie below the filter width are modeled. The scales separation is mathematically obtained by a filtering operation to the variable as:

\[ \bar{u}_i = \int \mathcal{G}(x,x') u_i(x') \, dx' \]  

(3.1)

where \( \mathcal{G}(x,x') \) is the filter Kernel (a localized function), resulting in \( u_i = \bar{u}_i + u_i^{SGS} \), where \( \bar{u}_i \) is the resolvable scale part and \( u_i^{SGS} \) is the sub-grid-scale part.

When the filtering operation is applied to the Navier-Stokes equation under the Boussinesq approximation in the written in Cartesian frame of reference becomes:

\[ \frac{\partial \bar{u}_i}{\partial t} + \frac{\partial \bar{u}_j u_i}{\partial x_j} = -\frac{1}{\rho_0} \frac{\partial p}{\partial x_i} + \nu \frac{\partial^2 \bar{u}_i}{\partial x_j \partial x_j} - 2\Omega_i \times \bar{\Omega}_i + \frac{\rho g_i}{\rho_0} - \frac{\partial \tau_{ij}}{\partial x_j} \]  

(3.2)

\[ \frac{\partial \bar{p}}{\partial t} + \frac{\partial \bar{p} \bar{u}_i}{\partial x_i} = k \frac{\partial^2 \bar{p}}{\partial x_j \partial x_j} \frac{\partial \bar{\rho}_j}{\partial x_j} \]  

(3.3)

\[ \frac{\partial \bar{\rho}_i}{\partial t} + \frac{\partial \bar{\rho}_j u_i}{\partial x_j} = \frac{\partial \lambda_{ij}}{\partial x_j} \]  

(3.4)

where Equations (3.2), (3.3) and (3.4) are continuity, momentum and density equations respectively. The over-bar symbol ‘\( \bar{\cdot} \)’ represents filtering operation by the LES methodology. In the Equation (3.2) and (3.3) \( u_i \) is the velocity component in direction \( i \)-direction (with \( i=1,2,3 \) corresponding to the streamwise (x), spanwise (y) and vertical (z) directions) \( t \) is time, \( p \) is kinematic pressure, \( v \) the kinematic viscosity of characteristic fluid, \( g \) is the gravitational acceleration, \( \Delta \rho \) is the density anomaly and \( \rho_0 \) the reference density. \( \Omega_i \) is the \( i \)-component of Earth’s rotation, \( g_i \) is the \( i \)-component of gravitational acceleration and \( \tau_{ij} \) is the SGS stress and \( k \) is the heat diffusivity. The effect of the small scales appears through the terms \( \lambda_{ij} = \bar{u}_i \bar{u}_j - \bar{\bar{u}}_i \bar{\bar{u}}_j \) in momentum equations and \( \lambda_j = \bar{u}_j \bar{\rho} - \bar{\bar{u}}_j \bar{\rho} \) in the scalar equation. They are called the SGS stress and the SGS density flux respectively.

### 3.3.2 The LES-WIND model

The equations for the usage of the code are solved in space and time using the fractional step formulation. The time integration is performed using the Adams-Bashforth method for the advective terms and Crank-Nicholson method for the diffusive term. Spatial derivatives are approximated with central differences, except the advective terms, which are discretized using the third-order accurate QUIK scheme. The effect of earth’s rotation is considered through inclusion of the vertical and horizontal background vorticity components. The code is structured to solve the variables on a non-staggered grid. The primitive variables, like velocity, pressure and density are located at the cell centroid, while at the cell faces the fluxes are defined [63].
Within previous sections we introduced LES-WIND code in simulating the atmospheric flow. We would consider and continue further on with assumptions that our initial field created with the LES-WIND for atmospheric flow is already verified [64]. Now, we would introduce the parameterization of surface roughness for the sea surface in order to create our atmospheric flow above the sea surface.

### 3.3.3 Wind profile over the sea surface

Estimation of the sea roughness and its dependence on sea state is challenging problem of air-sea interaction with several important applications, such as climate research and remote sensing. The bulk aerodynamic formulation connects the momentum flux at the surface $\tau$ to the mean wind speed at some reference level (usually at 10m) $U_{10}$ via drag coefficient $C_d$

$$\tau = \rho C_d U_{10}^2$$

(3.5)

where $\rho$ is air density. The variation in wind speed with height (wind shear) over land and water is typically described with the logarithmic law. Within a first approximation, a homogenous surface with neutral stability of atmosphere may be assumed. The mean wind speed, $U(z)$, at a height $z$ is thus described by:

$$U(z) = \frac{u_*}{k} \ln \left( \frac{z}{z_0} \right)$$

(3.6)

where $u_*$ is the friction velocity $k$ is the von Karman constant and $z_0$ is the roughness parameter. Between the surface and the first computational grid level the validity of Monin-Obukhov theory is assumed. The drag coefficient $C_d$ at 10m height is expressed as:

$$C_d = \frac{k^2}{ln^2(z_0)}$$

(3.7)

In contrast to land surfaces, the roughness of the sea surface is not constant. At any given time, the water surface roughness length varies with wave height and so is a function of wind speed and fetch (distance from shore). The Charnock model is often used for modeling the change in sea surface roughness length as a function of wind speed:
\[ z_0 = \frac{\alpha_c u_*^2}{g} \]  
(3.8)

Where \( g \) is the gravitational constant and \( \alpha_c \) is the Charnock constant. \( \alpha_c \) the Charnock parameter is usually assumed to be constant where various authors suggested the values ranging form 0.014 (Garratt, 1977) to 0.018 (Wu, 1980) and 0.035 (Kitaigorodkii, 1970). Here we would consider the expression for drag coefficient suggested by Wu (1980):

\[ C_d = (0.8 + 0.65 U_{10})10^{-3} \]  
(3.9)

In table 3.1 are summarized values of drag coefficient, the roughness length and friction velocity with respect to wind speed over the sea surface. Values of the roughness length of the order 0.010m commensurate with a mean wind speed of 40m.s\(^{-1}\) at 10m over the sea bear no relation to the physical scales apparent in a fully aroused sea.

<table>
<thead>
<tr>
<th>( \bar{u}_{10} ) [m.s(^{-1})]</th>
<th>( C_d \times 10^3 )</th>
<th>( z_0 ) [m]</th>
<th>( u_* ) [m.s(^{-1})]</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>1.45</td>
<td>0.0003</td>
<td>0.15</td>
</tr>
<tr>
<td>20</td>
<td>2.10</td>
<td>0.0016</td>
<td>0.84</td>
</tr>
<tr>
<td>30</td>
<td>2.75</td>
<td>0.0047</td>
<td>2.48</td>
</tr>
<tr>
<td>40</td>
<td>3.40</td>
<td>0.0103</td>
<td>5.44</td>
</tr>
<tr>
<td>50</td>
<td>4.05</td>
<td>0.0191</td>
<td>10.13</td>
</tr>
</tbody>
</table>

Table 3.1. Evaluation of surface drag coefficient, roughness length and friction velocity from equations (3.8) and (3.9) [66].

Consequently, the surface roughness length, \( z_0 \) increases with increasing wind speed. The air flow above the sea correspond to that over an aerodynamic smooth surface [65] and the roughness parameter is determined by the scale of molecular sublayer. In this thesis we consider roughness parameter, \( z_0 \), as smooth for open sea with the values of 1x10\(^{-4}\)m. This approximation if followed by Martinez Tossas and Leonardi (2013) and Melbourne and Blackman (1982). Comments about using approximation would be given in final Chapter of Conclusion and Future work. In Figure 3.2 the simulated wind profile is present for the mentioned sea surface roughness. From the presented figure we observe that the simulated field follows the logarithmic law.
In the following section, we would introduce the idealized case of horizontal axis wind turbine and the parameterization of turbine-induced force for the LES-WIND code for wind energy application.

3.4 Characteristics of wind turbine

For proposes of this thesis we will consider characteristics of the most commercial wind turbine called a horizontal-axis wind turbine, HAWT. A HAWT is sketched in Figure 3.3, described in terms of the rotor diameter $D$, the number of blades, the tower height $H$, the rated power, rotor swept area $A$, the characteristic drag and thrust parameters and power curve. The tower height is important since wind speed increase with height above the ground while the rotor diameter gives the available power of flow cross-section of area $A$ in extraction of the available power. The ratio between the rotor diameter $D$ and the hub height is often approximately one. The number of blades in most commercial HWAT wind turbine is usually two or three. A two-bladed wind turbine is often a downwind machine. We will consider behavior of an idealized wind turbine and presented an idealized HWAT turbine.
In Chapter 1, Section 1.2.4 we already introduced the theoretical power curve. The introduced values for cut-in, rated and cut-out wind speed would be used for our idealized wind turbine. The considered wind turbine have the power of 3MW, hub height of 100m, rotor diameter of 100m and a swept of the rotor us 31400m². The number of blades is 3 as the most common HWAT turbines and revolution per minute (rpm) of the turbine is set to 14.8. The analysis will shows an important concept and illustrates the general behavior of wind turbine rotors and the air-flow over them.

<table>
<thead>
<tr>
<th>wind speed [m/s]</th>
<th>Thrust coefficient Ct</th>
<th>wind speed [m/s]</th>
<th>Thrust coefficient Ct</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>0</td>
<td>15</td>
<td>0.25</td>
</tr>
<tr>
<td>4</td>
<td>0.82</td>
<td>16</td>
<td>0.2</td>
</tr>
<tr>
<td>5</td>
<td>0.8</td>
<td>17</td>
<td>0.18</td>
</tr>
<tr>
<td>6</td>
<td>0.8</td>
<td>18</td>
<td>0.15</td>
</tr>
<tr>
<td>7</td>
<td>0.8</td>
<td>19</td>
<td>0.12</td>
</tr>
<tr>
<td>8</td>
<td>0.081</td>
<td>20</td>
<td>0.1</td>
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<td>9</td>
<td>0.78</td>
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<tr>
<td>10</td>
<td>0.72</td>
<td>22</td>
<td>0.08</td>
</tr>
<tr>
<td>11</td>
<td>0.65</td>
<td>23</td>
<td>0.07</td>
</tr>
<tr>
<td>12</td>
<td>0.58</td>
<td>24</td>
<td>0.06</td>
</tr>
<tr>
<td>13</td>
<td>0.4</td>
<td>25</td>
<td>0.05</td>
</tr>
<tr>
<td>14</td>
<td>0.32</td>
<td>26</td>
<td>/</td>
</tr>
</tbody>
</table>

Table 3.2. Example of thrust coefficient curve depending on wind speed velocity [2].

Thrust coefficient is a non-dimensional coefficient highly depending on physical characteristics of wind turbine itself. Further on, we would consider theoretical values for thrust coefficient for our case of idealized wind turbine. Dependence of thrust coefficient with wind speed is given in the Table 3.2.
3.4.1 Parameterization of turbine-induced force

In this section we will introduce a parameterization of wind turbine that allows us to understand how the presence of the turbine in the numerical model creates a wake and modifies the characteristics of the flow. The simplified model for wind turbine is based on a linear momentum theory. Advancement in wind-turbine modeling was the introduction of the blade-element momentum (BEM) theory. This theory considers that each blade of a wind turbine can be divided into \( N \) blade elements, which are assumed to behave aerodynamically as two-dimensional aerofoils and to have no radial action on the flow. Based on momentum balance, the aerodynamic forces are determined using the lift and drag characteristics of the aerofoil as well as the local flow conditions. Note that, for each blade element, the lift and drag forces are perpendicular and parallel, respectively, to the direction of the local relative velocity. The resultant force is non-uniformly distributed on the blade surface or over the rotor-disk area, and produces thrust as well as rotation of the flow. This BEM approach can be applied into two types of wind-turbine models: actuator-disk model with rotation (ADM-R) and actuator-line model (ALM).

3.4.2 The Actuator Disc Concept for wind turbine

Use of an actuator disc approximation is a common approach to parameterize the turbine-induced forces in numerical models. A simple model, attributed to Betz (1926), can be used to determine the thrust force and the power production on an ideal turbine rotor and the effect of the rotor on the wind field. The basic idea of this theory is that turbine’s rotor is represented by ‘actuator disc’ through which the static pressure, but not the fluid velocity, changes abruptly. While detailed study of wind turbines can become quite involved, elementary theory can provide fundamental information in wind industry.

This idealized wind turbine model is based on a linear momentum theory. Several assumptions here need to be involved: wind is steady and homogenous, the disc is infinitely thin which means it is permeable for the air to pass through, the flow of fluid is considered to be incompressible, inviscid, irrotational and uniform at the upwind and downwind boundaries of control volume. Both the thrust and velocity are uniformly distributed on the disc and only the axial momentum balance is considered. Far upstream and downstream it is considered the ambient pressure.

We will consider a control volume fixed in space whose external boundaries are the surface of a stream tube whose fluid passes through the rotor disc, a cross-section of the stream
tube upwind of the rotor, and a cross-section of the stream tube downwind of the rotor. A simple scheme of this control volume is given in Figure 3.4.

![Figure 3.4](image)

**Figure 3.4.** Schematic presentation of thrust force of wind turbine [2].

We apply the characteristic of linear momentum theory and Bernoulli equation to the control volume enclosing the whole system to derive the net force on the contents of the control volume (Figure 3.4). Thrust force act in the streamwise direction resulting from the pressure drop over the rotor, and is used to reduce the wind speed after passing the rotor. The thrust force is then defined with Equation:

\[
F_T = -\frac{1}{2} \rho C_T U_{\infty}^2 A
\]  

(3.10)

Where in Equation (3.10) \( \rho \) is the air density, \( C_t \) is the thrust coefficient, \( A \) is a rotor swept area of a wind turbine \( (A = \frac{\pi}{4} D^2) \), where \( D \) is a diameter of a turbine) and \( U_{\infty} \) is the ‘upstream’ reference velocity far away upstream of wind turbine. Overall force is equal and opposite to the thrust, \( F_T \), which is the force of the wind on the wind turbine, as presented in Figure 3.4.

As for example, a high thrust coefficient \( C_T \) is present at low wind speed. The reason that the simple momentum theory is not valid is that free shear layer at the edge of the wake becomes unstable when velocity jump becomes too high and eddies are formed which transport momentum from the outer flow into the wake. This situation is called the turbulent-wake state [2]. In this thesis, the thrust coefficient \( C_T \) (Table 3.2) required to calculate the thrust force in the ADM-NR is used from the theoretical approximations and idealized case.

Since, the above mentioned methods only considers a uniform thrust load over the rotor disc and ignores the wake rotation effect, further on the mentioned method is referred as the
actuator-disk model without rotation (ADM-NR). This parameterization of wind turbines has been considered by other authors to represents well the far wake for the horizontal axis wind turbines (HAWT).

3.4.3 Implementation of wind turbine parameterization for LES-WIND

In this section we will present implementation of the parameterization of a wind turbine for the LES-WIND model. Previous section introduced a simplified model for the turbine-induced forces as the actuator disc model with no rotation. The implementation and new application of LES model is refer to IE-FLUIDS, spinoff of Department of Engineering and Architecture, University of Trieste.

Here, we would present the concept how to implement the induced-turbine force in LES-WIND model. In previous section we introduced the parameterization of ADM-NR considered for this thesis. Now we would apply the additional body force to the momentum equation (3.3) of our previously introduced Navier-Stokes equation as sink term. With this sink term we would be able to parameterize the turbine-induced forces and locally apply it on the flow. Then, momentum equation with representation of the impact for the wind turbines on the atmospheric flow would be:

$$\frac{\partial \mathbf{u}_i}{\partial t} + \frac{\partial \rho \mathbf{u}_i \mathbf{u}_j}{\partial x} = -\frac{1}{\rho} \frac{\partial P}{\partial x_i} + \nu \frac{\partial^2 \mathbf{u}_i}{\partial x_i \partial x_j} = 2\Omega_i \times \mathbf{u}_i + \frac{\mathbf{p}}{\rho} - \frac{\partial \tau_{ij}}{\partial x_j} + f_i \quad (3.11)$$

where in new momentum equation for wind turbine application we have additional force, $f_i$. Additional force is an immersed forcing used to simulate effect of wind turbine in the flow. The turbine-induced force $f_i$ is parameterized and integrated over the spatial and temporal scale in order to be applied to LES-WIND code. Than, thrust force (Equation 3.10) on a stencil of computational cell for standard actuator-disk model without rotation is calculated as:

$$f_k = -\frac{1}{2} \rho C_T \overline{U}_d^2 A \quad (3.12)$$

where $\overline{U}_d$ is the unperturbed streamwise velocity of the initial flow in the centre of the rotor disc, $A$ is the frontal area of cells within the rotor disc and $C_T$ is the thrust coefficient of the wind turbine specified in a Table 3.1. The parameterization of thrust force is followed by the approach of Wu et al. (2011). The parameterized forces are then smoothly distributed using a three-dimensional Gaussian approach to avoid singular behavior and numerical instability. The forces are distributed radially for every azimuthal position by taking the convolution of the computed local load, $F$, and a regularization kernel $\eta_e$

$$f = \frac{1}{\Delta v} (F \oplus \eta_e) \quad (3.13)$$
where

\[ \eta_e = \frac{1}{e^{3\pi/2}} \exp \left( -\frac{d^2}{e^2} \right) \]  \hspace{1cm} (3.14)

\( \Delta v \) is the volume of a grid cell, \( \epsilon \) is constant parameter that adjust the distribution of the regularized load, and \( d \) is the distance between grid points and blade elements. We have followed entire mentioned procedure and for the \( \epsilon \) and chosen a value equal to the grid-cell size in the streamwise (longitudinal) direction [52].

### 3.5 Numerical test

In this section, the initial numerical tests are carried out and the LES-WIND code with a wind turbine is considered. The test simulations are performed in two distinct phases. First, the atmospheric wind flow is generated by the LES-WIND solver, with switched off turbine parameterization in order to obtain the initial turbulent field. Then, the obtained initial filed was used to preform the simulations with one wind turbine with switched on turbine parameterization in LES-WIND code.

A simple orthogonal Cartesian coordinate grid is constructed, 300m long in the longitudinal (x-axis) and in the latitudinal direction (y-axis), and 600m stretched in the vertical direction (z-axis). The first computational grid in vertical direction is set to be at height of 2m and final 10m before the end of a vertical domain. With this assumption we would consider the Monin-Obhukov theory to be valid for the rest of the domain. The computational grid is discretized into 96x96x128 grid points. The lateral x and y planes of this computational grid are set to be periodic. With this periodicity the computational field is fed into the upwind boundaries, whereas the downwind ones become outflow boundaries. The inflow is forced with an inflow from the left in longitudinal direction and it is forced with a constant pressure gradient force. The lower boundary of the computational domain has imposed to no-slip condition while for upper boundary a free-slim condition is used.
One turbine for the initial test case is set to the centre of the lower boundary and it stretches upward to the hub-height of 100m. Figure 3.5 presents a sketch of the infinitive stretched wind farm and simulated domain of one turbine and its computational domain (with red rectangle). In Figure 3.6 we present the computational domain simulated with LES-WIND model.
Figures 3.6 and 3.7 present captured wake of the one turbine simulated with ADM-NR parameterization. Here, the distance in longitudinal (streamwise) and latitudinal (spanwise) directions between turbines in infinitively large wind farm is set to be 3 rotors diameters of a wind turbine. In this test case we observe that the inflow for the second turbine is strongly interrupted by the upwind turbine. This interruptions and wake effect would strongly reduce the extraction of the energy for every after downwind turbine. It is simple to deduce that turbine spacing in streamwise direction has to be larger than 3 rotors diameter of wind turbine, in order to wake recovery and maximize the energy production for the downwind turbine.

The vertical profiles of averaged velocity component $u$ obtained at $x$-$y$ cross-section in the central wake area for several distances of the turbine compared to initial filed (red color) are presented in Figure 3.8. With presented vertical profile, we capture the interruption of the flow field at various distance of the wake. At the turbine (black line) we observe the most intense interruption in the vertical profile at the height of 100 m (hub height). Vertical profiles strictly after the turbine (orange, purple color lines) have the highest interruption at the height of 150 till 200m heights while further on, vertical profiles further of the turbine have interruption of about 100m. The vertical profiles at various locations of the wake in general transect the theoretical vertical profiles at height of 400m. Still, with this test case, we cannot claim at which height there would disappear the interruption of the flow field imposed with the wind turbine.
Figure 3.8. Vertical profiles of time averaged $u$ component of wind obtained at points in the central wake area for several distances do the rotor layer.

Numerical simulations are computationally expensive. In this sense we only performed test simulation with one case wind conditions. Presented test case with one wind turbine gave an important step forward to create a theoretical offshore wind farm.

3.6 Results

3.6.1 Idealized wind farm

Theoretical wind farm counts 42 wind turbines of 3MW, with total power of 126MW. The grid resolution for simulation has 416x96x96 grid points 6240m x 800m x 800m. We positioned 6 wind turbines as presented in Figure 3.8, marked with red rectangle. Of particular importance are the longitudinal gaps between two successive wind turbines, i.e. the space available for the wake to recover before encountering other downwind turbines.
With this case, we simulate only a row of wind farm and assumed a periodicity just in lateral boundaries. With this procedure, we would be able to simulate entire wind farm with the approximation that no abrupt jump in velocity field is present in lateral axis far from turbine. This approximation is assumed according to performed test analysis where if prevailing wind is considered to be always perpendicular to the wind turbines, velocity field in lateral boundaries far from the turbines are not affect tremendously.

---

**Figure 3.9.** Sketch of an idealized wind farm wind farm

**Figure 3.10.** Representation of initial forcing filed direction (black arrow) for the simulation case of wind farm array.
The initial wind field was generated with the LES-WIND solver. The forcing field for the case with wind array was then taken from a horizontal cross-section of initial field. Then, the prepared forcing field was forced constantly from the left lateral boundary in longitudinal (streamwise) direction (Figure 3.9). Right lateral boundary in longitudinal direction was set to be open. Bottom boundary is set as no slip with usage of wall function while other boundaries are set free slip conditions. The periodicity is set in latitudinal direction.

We assumed that the prevailing wind is uniform and aligned with the rotor axis and that the blades rotate in a plane perpendicular to the rotor axis. These assumptions are rarely met in real case. The actual flow field, however, is much more complicated. Here, we simplified method for calculating the performance of a horizontal axis wind turbine rotor that is particularly applicable for an installed rotor, but may also be useful under certain stall conditions.

**Figure 3.11.** Longitudinal cross-section at centre of turbine’s array. Vertical black lines denote the position of the wind-turbine disks.

**Figure 3.12.** Horizontal cross-section at hub height of turbine’s array. Vertical black lines denote the position of the wind-turbine disks.
In figures 3.11 and 3.12 we present contours of instantaneous streamwise velocity in horizontal cross-section at the centre of turbines and at the hub-height. The turbine’s layout position is presented in both cross-sections. The first turbine is positioned at 400m from the beginning of the domain and sixth turbine at 4600m, where computational grid is 15m in streamwise direction. The distances between turbines are 800m and 1000m between first three and second three turbines in the array. The gap between turbine pairs is considered in length recovery of produced wake. From the presented figures it is easy to observe that at the first turbine, the non-perturbed wind is coming creating the wake afterwards. The most pronounced wake is created from the last turbine in an array. Here, we presented the test simulation of 6 turbines in array needed in a way of simulated entire wind farm of our sub-region of the Gulf of Lion.

3.6.2 Power estimation of idealized wind farm and regional analysis

In order to continue analysis and downscale regional data to the scale of wind farm, first we would assess differences between QuikSCAT satellite observations and PROTHEUS simulation of the wind speed. Figure 3.13 presents scatterplot of QuikSCAT and PROTHEUS for the sub-region the Gulf Lion considering the same time period of 9 years as in Chapter 2.

![Figure 3.13. Wind speed scatterplot of QuikSCAT and PROTHEUS for the sub-region the Gulf of Lion](image)

In the selected sub-region the Gulf of Lion wind speed at 10m simulated by PROTHEUS model is highly related to the QuikSCAT observed data of the same sub-region. The line of best fit drawn through the center of the data is presented on the graph in as straight
red line. The direction of correlation between the satellite and simulated wind data is positive and generally follows the straight line. The strength of correlation is moderately strong with the correlation coefficient of 0.7571. Mean values estimated by the model for the sub-region is 7.2 m.s\(^{-1}\) while for the QuikSCAT is 7.8 m.s\(^{-1}\). PROTHEUS model estimates standard deviation with the value 2.96 while QuikSCAT of 3.7. The measure of root-mean-square difference between model and satellite observation for the sub-region is 2.42.

Presented assessments between regional model and satellite observations allow us to move one step forward in our analysis. We selected from the database in Chapter 2 a day of 28\(^{th}\) April to downscale wind speed simulated with the PROTHEUS to the scale of wind farm using LES-WIND model. The date is chosen randomly.

Then, we would test and compare the estimations obtained with regional model of potential wind energy and simulated extracted energy from theoretical wind farm simulated with LES-WIND model. The orientation of theoretical wind farm is perpendicular to the orientation of the prevailing NW direction of Mistral winds. Figure 3.14 presents the average available potential energy estimated by the PROTHEUS model for the 28\(^{th}\) April.

![Figure 3.14. Map of estimated potential wind energy density for 28\(^{th}\) April by PROTHEUS model [W.m\(^{-2}\)]. In red rectangle the location of sub-region the Gulf of Lion is separated.](image)

The regional model estimate the average potential energy of the wind in the sub-region the Gulf of Lion of 400 W.m\(^{-2}\) at hub-height and the average mean velocity in the sub-region of 7.2 m.s\(^{-1}\) at 10m height. The spatial grid of the PROTHEUS model has resolution of 30 x 30 km, which is not sufficiently low resolution to be directly applied in the wind farm application. Theoretical wind farm presented in Figure 3.9 have spatial grid with dimensions of 6.24 x 4.8 x 0.8 km completely fallen in one spatial computational grid cell of the PROTHEUS model. In order to simulate the ‘real-case’ wind farm in the Gulf of Lion with the LES-WIND model we would create an inflow of constant prevailing wind speed with the information obtained with RCM.
Estimation of the available energy from the wind (wind power density) at specific location requires not only knowledge in mean wind speed [67]. During the years some days are calm, other days storms may be blowing, the wind will change during day and night, and in different seasons from year to year. For example, if the available energy at wind speed of 7m.s\(^{-1}\) is 215 W.m\(^{-2}\) according to the equation (1.6), we should make attention that the real site average energy from the 7m.s\(^{-1}\) mean wind speed in reality is about twice as large [68].

This fact is referred to the distribution of wind speed and cubic relationship between wind speed and wind energy content. Annual wind speed distributions vary widely from one site to another reflecting climatic and geographic conditions. However in mid-latitudes (entire Mediterranean basin and most parts of Europe) the wind speed distribution is well characterized with Rayleigh distribution [67]. This fact was used in regional analysis at Chapter 2 when we estimated available wind energy from the mean and not instantaneous wind speed (equation 2.3), where the correction factor was applied to the wind energy density equation.

In practice we can add a correction factor in order to calculate the energy content of the wind during the year from annual values. This correction factor (energy pattern factor) depends on the frequency distribution of the wind and it is referred to the shape of distribution function. The correction factor for the Rayleigh distribution is 1.91. Adding the correction factor in most cases will give a good idea of the wind’s energy in-situ content [67]; [68]. With this assumption we are able to estimate the mean energy from mean wind speed at specific location. Then, finalizing an above example of average wind speed of 7m.s\(^{-1}\) the energy weighted is referred to the average wind speed of 8.7m.s\(^{-1}\) where the power available is then 402 W.m\(^{-2}\). This is almost twice as much as we assumed in previous linear calculation.

The point we want to underline is that we cannot simply take the average of wind speed and then use the average value in wind energy estimations. The average wind speed alone does not provide enough information to determine energy potential; what is required is the distribution.

Now, we would consider mentioned concept of energy pattern factor for input mean wind speed obtained by RCM. Then, for the sub-region the Gulf of Lion we would consider the constant prevailing wind speed at 10m at velocity of 8.9 m.s\(^{-1}\) at 10m.

Figures 3.15 and 3.16 presents longitudinal contour of vertical and horizontal cross-section in the centre of the turbines and at hub height of turbine array for the sub-region of the Gulf of Lion. In both figures the wake of all turbines is well captured.
For every wind turbine the vertical profile of wind speed is presented at various positions capturing the wake and the profile of non-perturbed forced filed (in red) (Figure 3.17). All turbines reduce the velocity from the initial flow, where this speed reduction is the least for the first turbine. The vertical profiles in green color on Figure 3.17 represent the profile just before the turbine. The turbine’s wake is strongest expressed at the longitudinal distance of 100m for every turbine. For first two turbines vertical profiles at 200m height become to be close to the non-perturbed initial profile, while for other turbines in an array those height become larger, where for the last turbine in an array that height becomes even 300m.

Figure 3.18 it is captured near (2D) and far wake (4D and 6D) vertical profiles for all turbines. Far from the wake (6D), the perturbed velocity field is more uniformly distributed. The velocity minimum moved towards the center of the wake in the far wake. It however can be seen that the structured near wake reaches much further downstream in case of the undisturbed turbine compared to the other turbines of the wake. The velocity deficit is significantly stronger behind the second and subsequent turbines compared to behind the first turbine. From the second to the last turbine a slight recovery can be observed. The wake decays with downstream distance and it is considerably weaker in the centre of the wake.
Figure 3.17. Vertical profiles of time averaged longitudinal velocity component obtained at locations of the turbines for the sub-region the Gulf of Lion.

Figure 3.18. Vertical profiles of time averaged longitudinal velocity component obtained at 2D, 4D and 6D distances of the turbines for sub-region the Gulf of Lion.
In order to understand the longitudinal variation of the mean wind energy over chosen location, we performed averaging in time and vertical direction. Figure 3.19 shows the simulated mean wind energy density obtained over chosen location. From the contour plot we observe that first turbine on the left reduces the power in the wind flow up to 342 W m\(^{-2}\). The first turbine is able to reduce 42 W m\(^{-2}\) of energy from unperturbed wind flow. The first turbine is being able to reduce the highest amount of energy from all turbines in the array. Third, fifth and sixth turbines reduces the same amount of energy of 22 W m\(^{-2}\) from the flow, even thought the same amount of available energy does not faces mentioned turbines. The second turbine reduces 27 W m\(^{-2}\) of energy from the wind field while for the fourth turbine is observed extraction of only 18 W m\(^{-2}\). The energy extraction of forth turbine was expected to become much higher than observed in presented array design. The observed value of forth turbine is not clear in sense that we created much longer gap between third and fourth turbine in order that the produced wake of third turbine has more time to recover. The creation of longer gap between the turbines should arise in higher energy production of downwind turbine.

Within presented analysis we show that LES can provide reliable estimates of the overall mean wind energy inside wind farm. It is clear that mean energy production of the wind farm is affected by the wind farm layout. Based on averaging in time and vertical direction, we found the total power extracted by the turbine rotors considered ADM-NR parameterization.

3.7 Summary and conclusion

In the present Chapter we used LES-WIND, a numerical tool developed by IE-FLUIDS a spinoff of the University of Trieste, for wind energy applications. The aim is the evaluation of the available energy in wind farms where turbines are arranged in arrays, using a high definition...
numerical model able to predict realistically the interaction among the turbines coming from the development of wakes. The procedure to apply the turbine-induced force for wind application inside the LES-WIND model was followed by Wu and Porté-Agel (2010).

Large eddy simulation, coupled with a wind-turbine parameterization, has been used to simulate the wake of a wind turbine. The turbine-induced forces are parameterized using actuator disc model with no rotation (ADM-NR), which distribute the forces over the rotor disc. The ADM-NR calculates the thrust force based on the one-dimensional momentum theory and distributes it uniformly over the disc. With this simulation we wanted to describe many of the primary features of the air-flow into and around wind turbines, the induced velocities due to power production of the turbine wake and the expanding wake downwind of the turbine.

We compared available wind power density estimated with regional climate model and ‘real’ case scenario for the sub-region the Gulf of Lion of simulated offshore wind farm with LES-WIND model. Regional climate model and large-eddy simulation have generally quite different applications considering the physical characteristic of the models. In this sense, we considered one day test case (28th April) for simulating the offshore wind farm with LES-WIND model and used mean annual values from RCM for this specified day.

Although regional climate and local scale model have different physical characteristics and scope of interest, we could conclude that all together analysis gives valuable results. Within presented analysis, we could conclude that regional climate models good numerical tool and are able to provide information of potential available energy while local models provide real case scenario how much energy is extracted from potential available wind energy in the atmosphere. Additionally, performed analysis provides valuable procedure in providing the information in pre-planning a wind farm layout.

Presented analysis contributes in usage of both regional and local scale numerical models in wind energy application.
Conclusion and Future Work

The focus of this thesis was to present recent efforts to develop a multi-scale approach to assess proper location for offshore wind farms over the Mediterranean Sea. We propose regional climate models in order to analyze potential wind resources over the considered area and to select potential sub-regions for wind harvesting. Large-eddy simulation is proposed in order to perform localized analysis and parameterize real case scenario of theoretical wind farm over pre-selected sub-regions over the Mediterranean. In this way, we provided significant input information of wind climate for large-eddy simulation with regional climate simulations and large-eddy simulations provide appropriate parameterization of wind farm for climate models. In particular, deeper understanding in wind farm parameterization could be used for future forecast, seasonal or long-term projections of wind power production. Afterwards, this presented loop is of prominent importance if consider a warranted lifespan of wind farm of 20 years on land and of about 30 years offshore.

Analysis of regional climate simulations in Chapter 2 considered four models RegCM3; PROTHEUS; high-resolution WRF model (WRF11); low-resolution WRF (WRF44). QuikSCAT satellite observations have been used to compare model outputs. The regional results have been carried out to verify the reliability of climate model simulations in the reproduction of the most relevant features of present climate. The information from regional analysis was elaborated with the aim to find potential sub-regions for installation of wind farms over the region of Mediterranean Sea.

A wind resource atlas and maps of average number of days whose conditions lie within the wind turbine’s functional range have been presented over the basin. In order to indicate variability of the wind over the basin analysis of selecting wind events with different frequencies was performed to map diurnal, inter-seasonal and intra-annual variability. Following these results, first we reported potential sub-regions for wind application over entire Mediterranean basin and then we select three sub-regions for further investigation. The Gulf of Lion, the Sea of Crete and the North Adriatic are selected sub-regions as the most appealing potential areas for wind farms. Additional analysis considering regional models was performed in selected sub-regions focusing on the model’s skill in reproducing the wind considering the annual cycle and the intra-seasonal variability expressed in term of the probability density function of anomalies.

A methodological framework for providing future changes in the potential of wind power production using multi-model analysis was presented. Projection of future climate under A1B Scenario found decrease of wind power over the Mediterranean region, except of the
Aegean Sea. With this remarks we would like to include and justify the climate projections with regional climate models for wind power industry.

Local scale analysis in Chapter 3 was performed with large-eddy simulation model. We presented recent efforts to develop a large-eddy simulation framework (LES-AIR) for wind energy application. Turbine-induced force (ADM-NR) was implemented into the code LES-AIR to simulate the performance of created theoretical wind farm. We preform simulations in three sub-regions over the Mediterranean Sea pre-selected by regional analysis. By this, we created a valuable tool providing us in-depth information in better understanding of wake creation, flow propagation inside the wind farm and dependency of power production. The performance of offshore wind farms in the Gulf of Lion, the Sea of Crete and North Adriatic estimated with newly applied tool of LES-WIND code were compared with the estimations of the PROTHEUS model of wind potential.

The novelty of this thesis is twofold; up to now, QuikSCAT satellite observations and RCMs simulations have not been taken into account for wind energy application over the Mediterranean Sea and we presented a pioneering approach in applying the large-eddy simulations (LES-WIND) to wind industry. The research presented here constitutes a step towards the development of a robust computational fluid dynamics framework both regional and local for the study of offshore wind energy. There is still place for substantial improvements focused for future work.

- One of future plan consists in preforming a downscaling of regional climate model (the PROTHEUS) and QuikSCAT satellite observations with LES-AIR model. The downscaling would be performed with nesting procedure, where, LES-AIR would be driven by RCM. By this procedure LES-WIND model would use its own physics based equations to resolve the regional input data for specified locations or entire Mediterranean basin. Nevertheless the requirement of significant computational costs, this procedure would significantly accomplish obtaining the need in high-resolution wind data, both in time and space. Within this procedure we could contribute with a wind atlas of Mediterranean Sea with valuable information needed to the wind industry.

- The major limitation of the LES-WIND code resides in the treatment of the air-sea interaction. Here we considered roughness length as smooth for open sea and equal for all state of wind. Direct resolving of very complex air-sea interaction considering marine atmospheric boundary layer (MABL) would give significant improvement of LES-AIR and LES-COAST models and more future investigations in complex air-sea applications.

- At the moment, we only considered one parameterization of turbine-induced force for horizontal axis wind turbine. The future improvements would be to focus on testing different techniques of turbine-induced forces parameterizations considering horizontal axis turbines and
try to move step forward in parameterization of vertical axis turbines. Also, simulation of real case operating wind turbine and comparing simulations with observed data inside the wind farm or with possible experiments of wind-tunnel would be significant verification test.

- Up to now we only considered idealized wind conditions the flow passing perpendicular to the turbine. This is rarely the case in real atmospheric flows. To deal with the issue of various direction of prevailing wind speed, we could maintain the applied simplification and consider the tangential component of prevailing wind.

- As for final goals would be to focus and improve seasonal and long-term future predictions of wind needed for planning new wind farms. The same improvement in accuracy of short-term wind forecast is needed for operating of wind farm to create prediction tool in delivering the harvested wind energy. Better predictability of wind resources will help producers to meet delivery commitments in the power market. Improved accuracy of power production forecasts on various time scales will support power system operation and enable wind power producers to act in electricity market Those perspectives are one of significant importance for wind industry.
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Appendices

This work include material from many different disciplines, form meteorology, climatology, aerodynamic, engineering, numerical simulations etc. within each of these disciplines commonly accepted variables are used. Nomenclatures used in the text are listed by chapters. The units in text follow SI units, for example, length is in m, speed is in m/s, mass is in kg, density is in kg/m³, weight and force are in N, power is in W. Energy is referred as W rather than in J.

Abbreviations:

A.1 Chapter 1

EWEA - the European Wind Energy Association;
EEA - European Environment Agency;
cut-in – start range wind speed value of wind turbine;
cut-out – end range wind speed value of wind turbine;
rated wind speed - the wind speed at which is reached the rated output;
P - kinetic energy per unit time, or power;
E - wind power density;
A – swept of turbine rotor area;

A.2 Chapter 2

RCM - Regional Climate Models;
GCM - Global Climate Model;
QuikSCAT – NASA’s Quick Scatterometer, an Earth observation Satellite, measuring the surface wind speed and direction over the global oceans;
SRES A1B - IPCC Special Report on Emission Scenarios, scenario family A1B;
RegCM3 - Regional Climate Model Version 3;
PROTHEUS - atmosphere-ocean regional model for the Mediterranean basin;
OASIS - software allowing synchronized exchanges of coupling information between numerical codes representing different component of the climate system;

CCM3 - standalone version of the radiation model used in the NCAR Community Climate Model;

GHG - Green House Gasses;

MITGcm - Massachusetts Institute of Technology General Circulation Model;

ERA40 - ECMWF second generation re-analysis of global atmosphere for the time period Sep 1957 – Aug 2002;

WRF - Weather Research and Forecasting Model;

ERAInterim - ECMWF third generation re-analysis of global atmosphere for the time period 1979 up to near-real-time;

EURO-CORDEX - European branch of CORDEX initiative;


IPSL-LSCE - Institute Pierre Simon Laplace, Laboratorie des Sciences du Climat et de l’Environnement;

FFT - Fast Fourier Transform;

**A.3 Chapter 3**

CFD – computational fluid dynamic;

LES – Large-eddy simulation;

RANS - Reynolds Averaged Navier-Stokes Simulation;

DNS – Direct Numerical Simulation;

LES-AIR – in-house University of Trieste, large-eddy simulation model applied for atmosphere;

SGS – Sub-grid Scale;

$u_i$ - the velocity component in direction $i$-direction;

$t$ – time;

$p$ - kinematic pressure;

$\nu$ - kinematic viscosity of characteristic fluid;

$g$ - the gravitational acceleration;
\( \Delta \rho \) - the density anomaly;
\( \rho_0 \) - the reference density;
\( \Omega_i \) - the \( i \)-component of Earth’s rotation;
\( g_i \) - the \( i \)-component of gravitational acceleration;
\( \tau_{ij} \) - the SGS stress;
\( k \) - the heat diffusivity;
\( \tau \) - momentum flux at surface;
\( C_d \) – drag coefficient;
\( U_{10} \) – wind speed at 10m height;
\( u^* \) - friction velocity;
\( z_0 \) - the roughness parameter;
\( k \) - the von Karman constant;
\( \alpha_c \) - the Charnock constant;
HAWT - horizontal axis wind turbines;
\( D \) - rotor diameter of a wind turbine;
\( H \) - the turbine’s tower height;
\( A \) - rotor swept area;
\( C_t \) – thrust coefficient;
\( F_T \) – thrust force;
\( U_\infty \) - the ‘upstream’ reference velocity far away upstream of wind turbine;
ADM – actuator disc model;
ADM-NR – actuator disc model with no rotation;
\( \Delta v \) - the volume of a grid cell;
\( \epsilon \) - constant parameter that adjust the distribution of the regularized load;
\( d \) - the distance between grid points and blade elements;
ALM – Actuator line model;
BEM – Blade element momentum theory;