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Metocean data management and modeling to support U.S. offshore wind power development in the Mid-Atlantic

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**Metocean Data Management and Modeling to Support
U.S. Offshore Wind Power Development in the Mid-Atlantic**

Whitney West

A thesis submitted to the Graduate Faculty of

JAMES MADISON UNIVERSITY

In

Partial Fulfillment of the Requirements

for the degree of

Master of Science

Integrated Science and Technology

May 2012

Dedications

I would like to dedicate this thesis to my parents, Stephanie, Jerry, Toby, and Anne, for their unwavering support and encouragement; I could not have accomplished this without you all.

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Acronym and Abbreviation List

AEP – Annual Energy Production
API – Application Programming Interface
BOEM – Bureau of Ocean Energy Management
CAA – Cold Air Advection
CAD – Computer-Aided Design Program
DMME – Virginia Department of Mines, Minerals, and Energy
DOD – Department of Defense
DOE – Department of Energy
DOI – Department of the Interior
EA – Environmental Assessment
EEA – European Environment Agency
EIA – Energy and Information Administration
ESRI – Environmental Systems Research Institute
EWEA – European Wind Energy Association
FERC – Federal Energy Regulatory Commission
GDS – Geosciences Desktop Study
GHRSSST – Group for High Resolution Sea Surface Temperature
GIS – Geographic Information System
JMU – James Madison University
kWh – Kilowatt-hour
MAE – Mean Absolute Error
MBL – Marine Boundary Layer
MCP – Measure-Correlate-Predict
MMC – Multipurpose Marine Cadastre
MMS – Minerals Management Service
NCAR – National Center for Atmospheric Research
NOAA – National Oceanic and Atmospheric Administration
NOWTC – National Offshore Wind Test Center
NEPA – National Environmental Policy Act
NMM – Nonhydrostatic Mesoscale Model
NREL – National Renewable Energy Laboratory
NWP – Numerical Weather Prediction Model
NWS – National Weather Service
OCS – Outer Continental Shelf
ODU-CCPU – Old Dominion University Center for Coastal Physical Oceanography
OGC – Open Geospatial Consortium
PDF – Portable Document Format
PURPA – Public Utilities Regulatory Act

RAMS – Regional Atmospheric Modeling System
RFI – Request For Information
SST – Sea-surface Temperature
SSTdepth – Sea-surface Temperature at Depth ‘z’
SSTfnd – Sea-surface Foundation Temperature
SSTint – Interface Sea-surface Temperature
SSTskin – Sea-surface Skin Temperature
SSTsubskin – Sea-surface Subskin Temperature
VCERC – Virginia Coastal Energy Research Consortium
VCWE – Virginia Center for Wind Energy
VOWDA – Virginia Offshore Wind Development Authority
VT-ARI – Virginia Tech Advanced Research Institute
WCS – OCG Web Coverage Service Interface Standard
WEA – Wind Energy Area
WFS – OCG Web Feature Service Interface Standard
WMS – OpenGIS Web Map Service Interface Standard
WRF – Weather Research and Forecasting Model
WVD – Wind Vector Difference Error Term

Abstract

Efforts to encourage more conservative electricity consumption, through public awareness campaigns and government-mandated energy efficiency standards, have consistently been overshadowed by population increase and increased standards of living, leading to higher electricity demand, year after year. Sufficient resources and technology exist to support the development of a robust offshore wind industry to help meet this rising demand, but a number of barriers unique to the U.S. have hindered progress.

Addressing many of these obstacles involves resolving uncertainty issues related to development. Not only is there a general lack of data to provide stakeholders, developers, and governing authorities with sufficient information for informed decision-making for offshore wind projects, but the data that do exist are often fragmented or isolated within a particular project or application. There is an immediate need to improve the reliability of metocean data as it pertains to characterizing the offshore wind resource, and to share that and other related information in a standard format that promotes and encourages interoperability across multiple platforms associated with offshore wind development.

The methodology for addressing some of these data challenges began with the evaluation of a proposed improvement to a particular atmospheric modeling system being utilized to provide wind resource data within the “Virginia Offshore Wind Advanced Technology Demonstration Site Development” project. By considering the current limitations associated with SST data acquisition and initial analyses, it was determined that the integration of higher resolution SST data would be valuable only if latency issues in the data were resolved, which would require the development of an SST forecasting

mode to be coupled with the operational model. This did not prove justifiable due to the lack of significant improvements in wind speed forecasting capability. Data accessibility issues were then addressed in the development of a web mapping portal designed to dynamically display geo-referenced project results and integrate publicly-available metocean data. By utilizing best practices for data sharing and information dissemination, optimum interoperability was established through smart design and the use of standard web service protocols.

Chapter One: Introduction

According to the Energy Information Administration (EIA), electricity use in the United States has increased by more than thirteen times the consumption levels of 1950, totaling almost 3,884 billion kilowatt-hours (kWh) in 2010 (EIA, 2011b). The residential sector accounts for nearly 40% of the total electricity demand, used mainly for appliances and electronics, lighting, and air conditioning (EIA, 2011b). Federally mandated energy efficiency standards for most major appliances were introduced in the late 1980s and early 1990s, which significantly slowed the growth in electricity demand during the last two decades. Homes became more efficiently designed and required significantly less electricity for space and water heating, yet with the construction of nearly 35 million homes over the last three decades, the appetite for energy has continued to grow (EIA, 2011c).

Improved living standards have turned what used to be luxury appliances into household necessities; not only do consumers own clothes washers and dryers, dishwashers, and air conditioners, but they also now use numerous personal electronic devices, which offset the electricity savings from more efficient appliances. Many homes have one or more computers, multiple televisions with growing screen sizes and quality, video game consoles, and a variety of chargers for their mobile phones, handheld devices, and other electronics, all of which draw electricity from the grid. The modern industrial era is driven by information technology, and Americans have become highly dependent on electricity to fuel their lifestyles and ensure their security and future prosperity. In order for the U.S. to continue to meet ever-rising demand, it will need to incorporate

alternative energy options, such as wind and solar technologies, to maximize energy production while reducing dependence on its major source of primary energy, fossil fuels.

Only 8% of the energy currently produced in the U.S. derives from renewable sources; this translates to a heavy reliance on fossil fuels to meet national electricity, transportation, and heating needs (EIA, 2011a). In 2010, 37% of U.S. energy consumed was produced from petroleum, 25% from natural gas, and 21% from coal, while oil was the source of only 11% of the energy actually produced domestically (EIA, 2011a). Despite being the third largest crude oil producer in the world, nearly 50% of U.S. petroleum demand must be met through supplemental crude oil and refined petroleum imports (EIA, 2011e). Consumers will continue to demand cheap and reliable energy from power companies, but a continued reliance on foreign oil to meet these demands poses significant economic and security risks. Not only does it strongly influence U.S. foreign policy, but also threatens long-term economic recovery and growth since oil prices can be volatile and are vulnerable to the influence of unstable foreign governments (Beddor, C. et al., 2009).

Considering levelized energy costs alone, which represents an economic assessment of the cost in dollars, at present value, per megawatt-hour of the energy generated from a particular system, and except in the case of land-based wind farms, the cheaper cost of building new coal and natural gas facilities makes it difficult to justify economically a transition toward the incorporation of more renewable sources into the U.S. energy portfolio (EIA, 2011d). Other arguments against wind and solar technologies include reliability and intermittency problems, electricity transmission and grid interconnection issues, as well as the large surface area required by industrial-scale

projects. Although important considerations, these arguments fail to take into account the monumental environmental implications and safety risks associated with traditional energy production strategies, and the indirect environmental and health costs they impose on society as a whole.

Background and Introduction to Research:

Intermittency and energy storage issues prevent the energy produced by wind power from being able to immediately displace fossil-fuel sourced energy, but with nearly 200-GW of power-generating capacity worldwide by the end of 2010, wind power is currently one of the fastest-growing alternative energy technologies across the globe and stands to develop even faster as technological advances further increase reliability and reduce costs. Wind power not only reduces greenhouse gas emissions, but also diversifies our energy sources and creates jobs, thus advancing energy independence and security while enhancing economic prosperity. The offshore resource is enormously attractive because it can support greater electricity production per surface area than can land-based wind farms since the geographical complexities that influence wind speed and direction on land are not present, thus often resulting in winds offshore that are stronger, more consistent, and easier to predict.

Led by Denmark and the United Kingdom, Europe remains the world leader in terms of offshore wind capacity, with over 3.8-GW installed as of 2011 (EWEA, 2012a). The exponentially increasing number of European success stories over the last decade have stimulated the development of significant U.S. state and national interest in research and development of offshore wind. Although multiple offshore wind projects are

currently under development, as of early 2012 the U.S. still has not installed any offshore wind, and only one single project has been successfully permitted (Cape Wind, 2011).

Research Question

The promise of regulatory hurdles and intense project-specific opposition, both of which have and will continue to lead to costly delays, has essentially stagnated investment, if not interest, in American offshore wind development. To mitigate some of these issues while hoping to simultaneously kick-start the young, but promising, industry, the U.S. has recently developed a robust national strategy aimed at promoting and accelerating environmentally responsible offshore development in federal waters.

Although this is a step in the right direction, offshore wind power remains a relatively nascent technology, which means a very limited supply of critical data exists to provide sufficient aid in offshore development processes including site selection, wind resource characterization, permitting, design, manufacturing, installation, and operation and maintenance. The limited availability of reliable, but also accessible, data to address these issues can hinder market development and overall reduction of the cost of electricity from offshore wind, not to mention deployment timelines and investment risks. This dissertation addresses specific data challenges pertaining to the “Virginia Offshore Wind Advanced Technology Demonstration Site Development” project to demonstrate the importance of reliable and accessible data in reducing uncertainty and removing market barriers to offshore wind deployment.

Phase One

High quality measured and predicted metocean data are vital to understanding real wind and water conditions at proposed wind farm locations. Phase One of this effort aims

to demonstrate the need for reliable forecasting models in wind farm site assessment. Model projections are utilized by developers, operators, and other stakeholders to provide accurate, in-depth assessments of wind characteristics in a proposed area at any given time and under any meteorological conditions. Although atmospheric models can only estimate the varied influences that contribute to wind behavior, model projections are valuable and are continuously analyzed and verified, and model updates are generated through the use of historical and real-time observational data.

The Regional Atmospheric Modeling System (RAMS) uses a set of dynamic equations that govern atmospheric motion, as well as a number of optional parametrizations to simulate and forecast meteorological phenomena on the scale of meters on up to hundreds of kilometers. Using the WeatherFlow Regional Atmospheric Modeling System (WRAMS), influences from geographical terrain and land use are combined with proprietary and public observational and remotely-sensed atmospheric data to provide reliable mesoscale wind models at high resolutions. Additionally, in micro-scale forecasts of specific locations, such as the three near-shore test sites under study in the “Virginia Offshore Wind Advanced Technology Demonstration Site Development” project, WRAMS takes into account traditional factors as well as more subtle influences that affect wind behavior, including cloud cover, precipitation, soil moisture, and sea surface temperature.

Even with substantial increases in computational speed, the density and quality of input data, together with the inability to exactly solve the equations used in atmospheric models, introduces errors that limit model projections. As more reliable and higher resolution datasets are becoming available for these micro-scale model inputs, experts

must analyze how utilizing them may affect their models, as well as whether higher resolution actually translates to increased reliability. This will help determine how to balance input data with forecast accuracy in order to determine the practical limits of a particular atmospheric model.

Specifically, the work reported in Phase One of this dissertation addresses an analysis of the effects of integrating an improved resolution sea-surface temperature (SST) dataset into WeatherFlow's WRAMS forecasting model. It has been hypothesized that the higher resolution 1-km SST datasets will be closer in value to the observed SST than the 9-km resolution SST datasets that are currently utilized, based on the assumption that higher resolution data should, generally, reflect greater accuracy. An analysis of how the 1-km and 9-km datasets compare to the measurements gathered in situ during one of eight annual subseasons is intended to assist in determining whether the higher resolution datasets should be used as an input into the WRAMS model to improve Weatherflow's numerical weather predictions.

Phase Two

Although important, the improvement in the reliability of data used in wind farm development is useless if it is subsequently restricted from use by interested parties. Individual offshore or coastal wind projects and research efforts may use or create various levels of proprietary and publicly available data, but such data must be organized and communicated in a way that encourages national, regional, and local collaboration in order to maximize its effectiveness. This is the main subject of Phase Two of this dissertation. Distributed systems, such as the internet and the World Wide Web, connect computers and users to each other through an online communication network, and help

coordinate the use of shared resources. These systems can be utilized to encourage and facilitate sharing of wind and other data, thus leading toward a common goal of establishing an offshore wind industry in the U.S.

Web-based applications are computer software accessed over a distributed system that help a user perform tasks through a web browser rather than through their individual computers. These applications are generally structured in an “n-tiered,” service-oriented approach, which separates components of an application based on their individual roles. The three main tiers are presentation, application, and storage. In this general format, the user accesses a web browser (presentation tier), which sends requests to a web service (application tier). The web service then processes those requests through queries to a database (storage tier), or other web applications, and communicates them back to the browser through an application program interface (API). Protocols, or standard methods for transmitting data, exist for web services that promote the sharing and distribution of information between collaborating services within a network. There are many different specialized protocols to accommodate the various types of data that might be transmitted.

The Open Geospatial Consortium (OGC), a voluntary international organization comprising nearly 300 governmental agencies, companies, and academic institutions has helped to develop and implement a set of open standards for publicly available geospatial data. OGC web services represent a standards-based, interoperable framework that allows distributed geoprocessing systems to communicate with each other. Of the more than thirty-five OGC web service protocols that currently exist, three are of particular interest in this application: web mapping services, which transmit map images only; web

coverage services, which stream raster data; web feature services, which stream vector data such as points, lines, and polygons.

One of the deliverables within the scope of the “Virginia Offshore Wind Advanced Technology Demonstration Site Development” project is to create a web page dedicated to the broader efforts that support other appropriate internet-based techniques for information dissemination and communications. To support this, a major element of this dissertation is to help design a web mapping component of the website that will display project results and integrate distributed metocean data from other locations through web services to be visualized within the map. The importance of making wind energy information available through standard services that ensure interoperability is paramount, so that it can be accessed, manipulated, and enhanced for future applications, despite whatever the limited data requirements may be within an individual project.

Methods and Key Findings

Efforts to encourage more conservative electricity consumption, through public awareness campaigns and government-mandated energy efficiency standards, have consistently been overshadowed by population increase and increased standards of living, leading to higher electricity demand, year after year. Sufficient resources and technology exist to support the development of a robust offshore wind industry to help meet this rising demand, but a number of barriers unique to the U.S. have hindered progress.

Addressing many of these obstacles involves resolving uncertainty issues related to development. Not only is there a general lack of data to provide stakeholders, developers, and governing authorities with sufficient information for informed decision-making for offshore wind projects, but the data that do exist are often fragmented or

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Overall Structure of Dissertation

The following chapters of this dissertation will aim to demonstrate the importance of reliable and accessible data in overcoming the barriers to offshore wind development in the U.S. Chapter two will set the context for the research, providing a brief history of

European offshore wind farm development, highlighting U.S. land-based and offshore wind resource potential, and identifying barriers that have hindered U.S. offshore development and how they are being addressed at both a federal and state level. It will also introduce the scope of work for the “Virginia Offshore Wind Advanced Technology Demonstration Site Development” project.

As the first of two chapters dedicated to Phase One, Chapter 3 describes some of the basic concepts associated with meteorology, atmospheric models, and sea surface temperature, in an effort to demonstrate the importance of air/surface interactions in weather prediction. From this, it introduces the hypothesis that the incorporation of higher level SST data will improve WeatherFlow’s RAMS forecasting ability, and provides a methodology for testing. Chapter 4 first presents the results and implications of the initial mean absolute error analysis. Time-lag issues are then identified and corrected, and further error analysis is used to determine changes in accuracy. Finally, model re-run performance, utilizing corrected SST data, is evaluated with meteorological verification statistics and the overall value of integrating 1-km SST data is discussed.

Chapter 5 encompasses the work associated with Phase Two, beginning with an introduction to Geographic Information Systems (GIS) and the structure of distributed systems, as well as an explanation of methods for data sharing and the importance of interoperability standards. These concepts are then practically applied in the development of a web portal, through both custom-built APIs and standard web services, used to dynamically display wind resource and energy potential, as well as integrate and display project data with other relevant open source data pertaining to the “Virginia Offshore Wind Advanced Technology Demonstration Site Development” project. Chapter 6 is a

concluding section which summarizes the results, and discusses how they address data reliability and accessibility issues as well as general implications for offshore development in the U.S.

Chapter 2 - Development of an Offshore Wind Market in the U.S.

History of development in Europe

While harnessing wind power for over 20 years, Europe remains the world leader in offshore wind development. Recent estimates from the European Environment Agency (EEA) suggest that offshore wind energy has the potential to provide seven times the current electricity demand in Europe (EWEA, 2012b). With nearly 75% of that resource potential (<30 km from shore) concentrated in the Baltic, the North Sea, and the Mediterranean, there has been rapid development in those areas over the last few years (EWEA, 2012b).

In 1991, Denmark became the first country in the world to successfully install turbines in the water. The 4.95-MW Vindeby Offshore Wind Park, built by Siemens Wind Power (formerly Bonus Energy A/S), consists of 11 turbines in depths of up to five meters, and recently celebrated its twentieth year in operation (EWEA, 2010). This early success sparked further development in Denmark, which remained the sole investor in large-scale offshore wind power for more than a decade after Vindeby was completed. One of Denmark's more notable farms includes the 80-turbine, 160-MW Horns Rev wind farm, which was constructed in 2002. Its expansion, Horns Rev II, was completed in 2009, adding 90, 2.3-MW turbines and increasing installed capacity by 209-MW (4COffshore, 2012a). The 166 MW Nysted wind farm started operation in 2003, and its expansion, completed in 2011, added another 207-MW of installed capacity (4COffshore, 2012bc). At the end of 2011, Denmark had 13 operational wind farms with a combined installed capacity of 857.3-MW, amounting to 23% of the cumulative installed capacity

in Europe (EWEA, 2012a). Further, Danish wind turbine manufacturers Siemens Wind Power and Vestas remain major industry players, having installed over 90% of global offshore capacity as of 2010.

With over 2000-MW installed by the end of 2011, and representing more than 50% of global installed capacity, the United Kingdom (UK) remains the current world leader in offshore wind (EWEA, 2012a). Joining the market more than ten years after Denmark, the 30-turbine, North Hoyle wind farm brought the first 60-MW of installed capacity to the UK in 2003 (Vestas). When the 194-MW Lynn and Inner Dowsing wind farm came online in 2009, the UK surpassed Denmark with installed capacity and has since remained the world leader in offshore development. Other notable UK installations completed over the last two years include Walney and Thanet, the first and second largest wind farms in the world, with 367 and 300-MW installed capacity, respectively.



Figure 1: European Offshore Wind Installations
Source: <http://contrarian.ca/2009/11/28/visual-data-wind-power/>

Although Denmark and the UK continue to dominate the offshore market with 31 cumulative wind farms, eight other European nations have recently completed their own offshore installations. To date, there are a total of 22 operating European offshore wind farms in waters off the coasts of Belgium, Finland, Germany, Ireland, the Netherlands, Norway, Sweden, and Portugal (EWEA, 2012a), as shown in Figure 1 above. In addition to the 3,812-MW total operating capacity in Europe at the end of 2011, nine offshore projects currently under construction will add 2,375-MW of capacity once completed (EWEA, 2012a). An additional nine projects under various stages of development, of which over 2,200-MW are within German waters, would increase Europe's cumulative capacity to over nine gigawatts (GW), setting it well on its way to meeting the European Wind Energy Association (EWEA) target of 40-GW installed capacity of offshore wind by 2020 and 150-GW by 2030 (EWEA, 2012ab). Europe's commitment to clean energy through its rigorous climate goals has stimulated major offshore wind energy development over the last decade, creating thousands of new jobs, promoting more efficient technologies, and creating an international market.

In 2010, China built the first commercial-scale offshore wind project outside of Europe. The Donghai Bridge Wind Farm comprises 34, 3-MW turbines, providing 102-MW of installed capacity (Patton, 2012). A number of other commercial, pilot, and demonstration projects are currently under development in hopes of helping reach China's lofty goals of 5-GW of offshore power by 2015 and 30-GW by 2020 (Patton, 2012)

U.S. Offshore Wind Resource Potential

As Europe continues to successfully develop its offshore wind market, the U.S. has begun to take serious notice of the potential for energy production off its own coastlines. In July 2004, the National Renewable Energy Laboratory (NREL) released a report entitled “Future for Offshore Wind Energy in the United States,” which was among the first to begin to address changing national and state perspectives on the prospect of incorporating offshore wind into the U.S. energy portfolio (NREL, 2004). Among other things, this report highlights the drawbacks of focusing solely on land-based wind, noting cost and efficiency challenges associated with transmission. Despite the vast resource potential available onshore, the distance from areas most suitable for wind projects to large load centers can be a limiting factor for development. Using a compilation of historical wind data, AWS Truepower, in collaboration with NREL, created the map shown in Figure 2 below describing the overall onshore wind resource potential within the U.S.

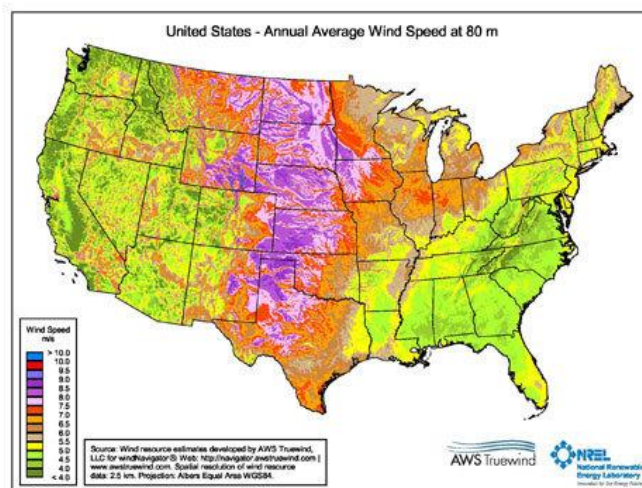


Figure 2: U.S. Annual Average Wind Speeds at 80 m
Source: <http://www.rechargenews.com/energy/wind/article206727.ece>

Although the U.S. has a substantial wind resource, a majority of this potential resides in the windy, midwestern regions. Until recently, offshore wind development has been overshadowed by the vast potential for land-based facilities to help meet the nation's electricity needs. However, higher electricity demands exist in urban areas near the coast, presenting increasing transmission challenges for inland, land-based wind facilities. In June 2010, NREL released a report entitled "Assessment of Offshore Wind Energy Resources for the United States," which compiled data on wind speed, water depth, and distance from shore, and used GIS techniques to create annual average wind speed maps to provide an estimate of the offshore wind resource potential (NREL, 2010). To accomplish this, potential capacity was calculated at a height of 90 meters for the total offshore area within 50 nautical miles of shore where annual average wind speeds are at least 7 meters per second, and assumed that a 5-MW turbine to be placed in every square kilometer of suitable area (NREL, 2010). The report gives a rough estimate of gross wind resource for each of the 26 coastal states, broken down by wind speed and water depth. Taken together, the U.S. has the potential for 4,150 GW of potential installed turbine capacity, approximately four times its current electricity demand (NREL, 2010). This estimate, however, reflects the gross wind resource, and does not consider exclusion areas such as environmentally protected areas, military training sites, or areas of heavy vessel traffic, among others, which may significantly reduce the viable resource potential available.

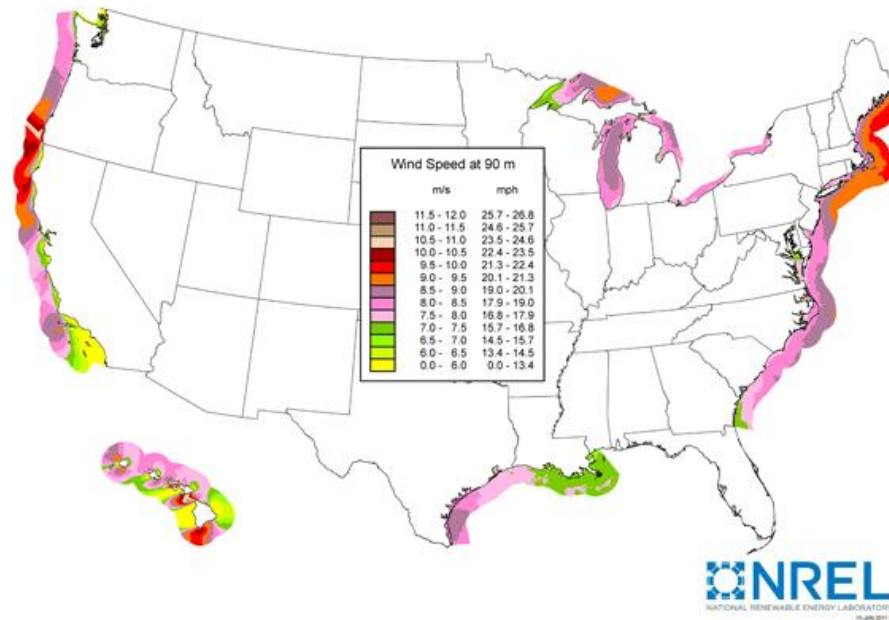


Figure 3: U.S. Annual Average Offshore Wind Speeds at 90 m
 Source: <http://205.254.135.7/todayinenergy/detail.cfm?id=4770>

In addition to the absence of the geographical terrain influences that affect land-based wind, the higher resource potential and proximity to coastal load centers make offshore wind energy an attractive, viable option for the U.S. As the map in Figure 3 above indicates, a majority of the offshore wind resource potential is located in the Pacific, Gulf Coast, Great Lakes, and Atlantic regions. Figure 4 below shows the bathymetry along U.S. coastlines, which demonstrates very deep waters along the Pacific Coast. Due to water depth constraints given the current state of the technology, most interest in commercial development, for the time being, excludes the Pacific coast. Although Europe is now experimenting with deepwater installations, the majority of installed capacity to date is in waters not deeper than 30 meters, and the U.S. is more likely to concentrate on areas where the technology and experience already exists to aid the initial penetration into the offshore wind industry.

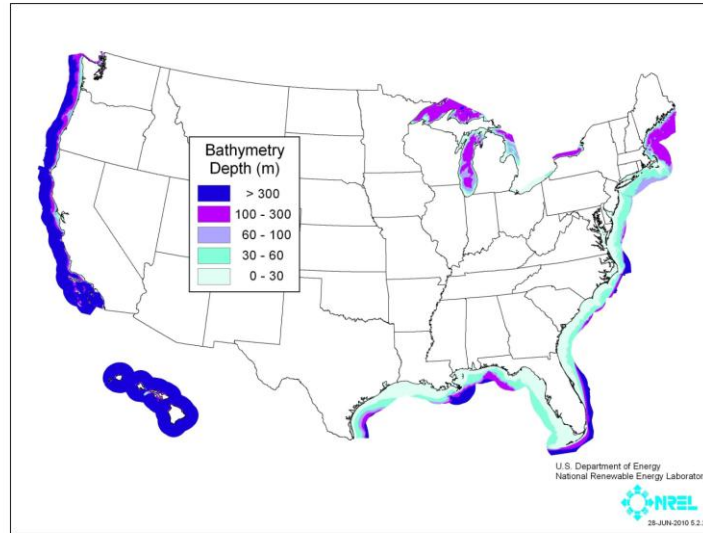


Figure 4: U.S. Bathymetry Distribution
 Source: <http://www.nrel.gov/docs/fy10osti/45889.pdf>

Development of National and State Interest

Despite facing many of the same challenges other renewable industries have overcome, offshore wind has yet to become a reality in the U.S. Sufficient technology and resources exist to create a successful offshore industry, but policy challenges unique to the U.S. have slowed development almost to the point of stagnation. National support for renewable energy in general over the past 30 years has been unstable at best, with interest rising and falling in response to fluctuations in oil and natural gas prices (Martinot, et al., 2005). The introduction of the Public Utilities Regulatory Act (PURPA) in 1978 led to the addition of 12,000-MW of renewable power to the U.S. electricity grid, but investment waned in the 1980s, as natural gas prices eventually declined (Martinot, et al., 2005). The late 1990s saw a renewed interest, with the introduction of new state energy policies, voluntary renewable portfolio standards, public benefit funds, and net metering programs. There have also been a number of subsidies, tax credits, rebates, low-

interest loan options, and other financial incentives over the years that have provided additional support for mainly land-based wind and solar development (Martinot, et al., 2005).

20% Wind Energy by 2030 Goals

Like their onshore counterparts, offshore wind energy developers and manufacturers need policy assurance, in the form of strong market drivers and federal investment, to develop the abundant U.S. offshore energy resources. Efforts to significantly increase wind power generation on- and offshore have focused on addressing the barriers to further development. In a joint effort with government and industry leaders, as well as prominent national laboratories, the Department of Energy (DOE) released a report in July 2008 entitled “20% Wind Energy by 2030.” This modeled energy scenario provided a collaborative assessment of the costs, challenges, and potential impacts associated with wind providing 20% of U.S. electricity by 2030, of which 54-GW was proposed to come from offshore installations (DOE, 2008). While both the technology and resources exist to support offshore wind deployment, a lack of sufficient policy remains one of the main challenges to development.

Permitting Development

Recent efforts to change the existing regulatory framework have improved the outlook for offshore wind, but getting to this point has taken nearly twenty years. Prior to the Energy Policy Act of 2005, there was limited legal framework for offshore wind development in federal waters. The Energy Policy Act of 2005 officially granted permitting authority to the Bureau of Ocean Energy Management (BOEM), formerly the Minerals Management Service (MMS), for renewable energy projects and related uses of

the Outer Continental Shelf (OCS) (AWEA, 2011). It entrusts the Department of the Interior (DOI), through BOEM, the authority to grant property leases, easements, and rights-of-way for the purpose of offshore renewable energy development (AWEA, 2011). However, it was not until four years later that the DOI officially finalized the framework, or rules, to guide renewable energy development on the OCS.

In his 2009 Inaugural address, President Barack Obama called for the expansion of renewable energy development in the U.S. to combat climate change and increase energy security. His plan, “New Energy for America,” included a \$150 billion federal investment over the next ten years to promote clean energy development, with goals of doubling the nation’s renewable energy supply by 2013 (DOE, 2009). Within the first hundred days of his administration, President Obama, together with Secretary of the Interior Ken Salazar, announced the completion of the comprehensive regulatory framework governing renewable energy development on the OCS. Under this framework, all companies are required to first obtain a lease through BOEM; at which point the Federal Energy Regulatory Commission (FERC) then has authority over wave, current, and other hydrokinetic projects, while BOEM is granted exclusive jurisdiction over the construction, operation, and transmission of energy from all wind and solar projects (DOE, 2008). In addition to establishing a working framework, the program encourages further collaboration between federal, state, and local agencies to help utilize OCS renewable energy potential.

While the successful creation of a regulatory framework has been a major step in the right direction, the overall permitting process for an offshore wind project under the framework spanned across multiple regulatory agencies and included a number of

redundant requirements, and was still estimated to take at least seven years (Craig, 2011). This has created a high level of uncertainty for interested developers, which, when combined with high capital costs and the possible expiration of federal incentives for development, makes investment in offshore wind a risky proposition.

‘Smart from the Start’ Wind Energy Initiative

To address this issue, Ken Salazar launched the ‘Smart from the Start’ wind energy initiative in November 2010 for the Atlantic OCS to facilitate an accelerated, but thorough, leasing and approval process for new offshore wind projects (DOI, 2010). A number of Wind Energy Areas (WEAs) were identified along the Atlantic coast particularly suitable for development, which involved organizing the collection and analysis of information from state agencies regarding the environmental and geophysical attributes, as well as other uses, of key offshore areas (DOI, 2010). These data have been digitized and made publicly available for the benefit of potential investors and lease applicants. The initiative aims to simplify the approval process for proposed wind energy projects by eliminating unnecessary regulatory requirements which have prevented current projects from securing leases and moving forward. In addition, ‘Smart from the Start’ encourages the development of offshore transmission lines to be ready for the transport and dissemination of electricity once a wind farm is constructed (DOI, 2010).

The process of identifying WEAs has involved a major collaborative effort between BOEM and state and local governments, facilitated through the creation of interagency state task forces established in nine of the thirteen states along the Atlantic coast (DOI, 2010). These renewable energy task forces are made up of representatives from a number of key interests, including BOEM, the Department of Defense (DOD), the

DOE, the Army Corps of Engineers, etc, and a range of state agencies. They have provided invaluable assistance in the collection of crucial baseline information regarding the potential WEAs, helping identify resource and user conflicts that would preclude development. BOEM also published a number of Requests for Interest (RFI), or Calls for Information depending on the state, to solicit public comments regarding the suitability of the proposed WEAs and whether they require modification or refinement, as well as to gauge initial developer interest (DOI, 2010). To date, six WEAs have been officially defined; four off the coasts of Delaware, Maryland, New Jersey, and Virginia respectively in February 2011, and two more off the coasts of Rhode Island and Massachusetts in February 2012.

One of the most significant milestones perhaps for offshore wind development to date occurred in February 2012. A year after BOEM announced its intent to prepare a mid-Atlantic Environmental Assessment (EA) through the National Environmental Policy Act (NEPA) for commercial wind leases and site assessment activities within the first four WEAs, the assessment was completed with a finding of ‘No Significant Impact’ (FONSI) (BOEM, 2012b). This indicated that leasing WEA sites for offshore wind would have no significant impact on the environment, a step toward federal approval for wary developers. Although the EA does not address individual projects, it reduces uncertainty and reflects a general notion of regulatory support for offshore wind development that may encourage leasing interest. The EA also allows BOEM to move forward with leasing processes within the WEAs covered by the assessment. Shortly following the decision, Calls for Information and Nominations were made for Virginia, Massachusetts, and Maryland to solicit lease nominations. Depending on the number of interested developers

for each state, BOEM will respond with either a non-competitive or auction-based leasing process.

Development in Virginia

In 2010, Virginia created The Virginia Offshore Wind Development Authority (VOWDA) to promote, coordinate, and provide support for offshore wind energy and supply chain development in Virginia. Among a variety of efforts, VOWDA was charged with collecting and maintaining metocean and environmental data and ensuring that development does not conflict with other ocean uses or endanger avian or marine wildlife. The collaborative effort between Virginia and the appropriate federal agencies led to the development of a federally recognized WEA, shown in Figure 5 below. Beginning 23.5 nautical miles from the coast, the WEA includes nineteen whole OCS lease blocks and thirteen sub blocks, constituting nearly 113,000 cumulative acres (BOEM, 2012a).

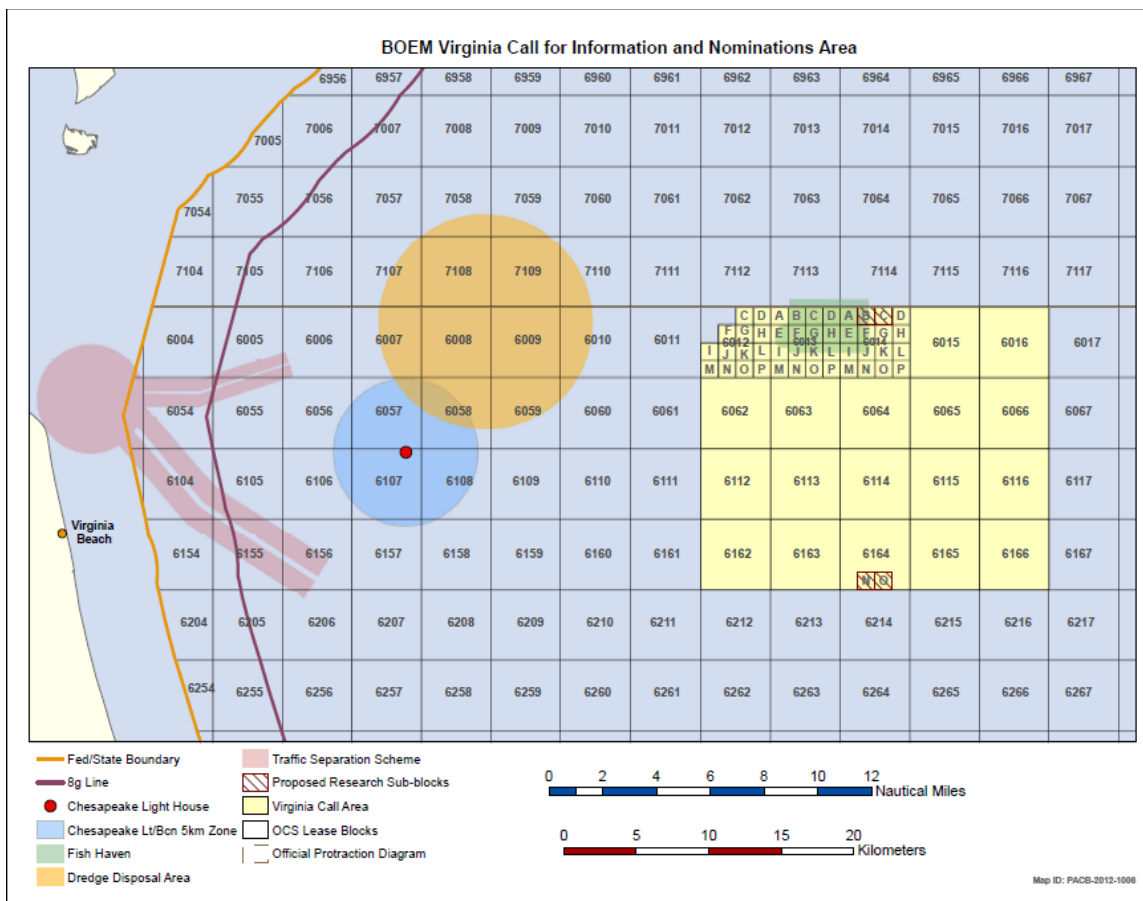


Figure 5: Map showing Virginia Call Area

Source: http://boem.gov/uploadedFiles/BOEM/Renewable_Energy_Program/State_Activities/V_A%20Cal%20Map%20without%20NOAA%20chart.pdf

In addition to contributing to these baseline studies within its WEA, Virginia has concurrently been participating in a variety of additional activities over recent years to help position itself to attract potential investors to develop offshore wind in the Commonwealth. One such activity involves developing near-shore advanced technology demonstration and testing sites for offshore turbines in state waters near the Chesapeake Bay. In June 2010, the DOE released a Request for Information (RFI) soliciting input on research, development, and deployment of offshore wind demonstration projects in hopes of stimulating offshore industry development in the U.S. Through the DOE’s Wind

Program, the RFI encompasses advanced technology demonstration projects as well as research aimed at addressing market barriers and cost reduction (BOEM, 2012b).

Virginia's Capstone Response outlined its efforts associated with offshore wind development, through baseline studies of offshore wind energy potential in state and federal waters, collaborative efforts with BOEM and other coastal states, and plans for the development of an advanced technology demonstration program. The Response suggested that Virginia was in a unique position to work with DOE to develop an advanced technology demonstration program leading to the eventual establishment of a National Offshore Wind Test Center (NOWTC) (DOE, 2010). Full-scale demonstrations of advanced technologies would help eliminate a number of technical challenges to commercial development, promoting cost-effective projects in Virginia and other areas in the U.S. (DOE, 2010).

In April 2011, two complimentary proposals, "Accelerating Virginia's Offshore Wind Economic Development," and "Offshore Wind Test Site Development Effort" (now called the "Virginia Offshore Wind Advanced Technology Demonstration Site Development" project), were submitted to, and approved by, the Virginia Department of Mines, Minerals, and Energy (DMME). The proposals were submitted by Virginia Tech Advanced Research Institute (VT-ARI) and James Madison University (JMU) respectively, both under the auspices of the Virginia Coastal Energy Research Consortium (VCERC). Cumulatively, they received over \$1.3 million from the DMME to fund these efforts with an ultimate collaborative goal of accelerating the development of offshore wind in Virginia. The study conducted by VT-ARI focuses on establishing Virginia as the central hub for manufacturing, logistics, and supply chain needs for

offshore wind development in the Mid-Atlantic. It evaluates Virginia's existing facilities for manufacturing and interconnection, prepares a workforce development plan, and includes the development of a business plan for the proposed NOWTC.

The "Virginia Offshore Wind Advanced Technology Demonstration Site Development" project represents a compliment to VT-ARI's work, in that they are both aimed at jumpstarting offshore wind industry development in Virginia so that it will be well positioned to accommodate future commercial projects in its WEA. Through the DOE's Wind Program, the effort would serve as a foundation for the development of advanced technology demonstration projects to further industry knowledge and support local industry development. Figure 6 shows the three locations off the Virginia Coast and in state waters that were identified as proposed sites for development; east/southeast of the Chesapeake Bay Bridge Tunnel Fourth Island, just offshore of the Newport News wave screen to the east of the Monitor Merimac Bridge Tunnel north end, and north/northwest of the former Tidewater Community College site in Suffolk to the west of the Monitor Merimac Bridge Tunnel south end.

At each of three proposed locations, the primary project tasks include analyzing the technical feasibility of near-shore turbine test and demonstration pad sites, metocean resource characterization, community outreach and stakeholder engagement with wind industry members, and preparation of the necessary documentation to proceed with permitting. The results of these studies are meant to provide the groundwork to more easily facilitate permit acquisition by a private sector entity interested in developing an offshore wind turbine testing and demonstration capability in Virginia.

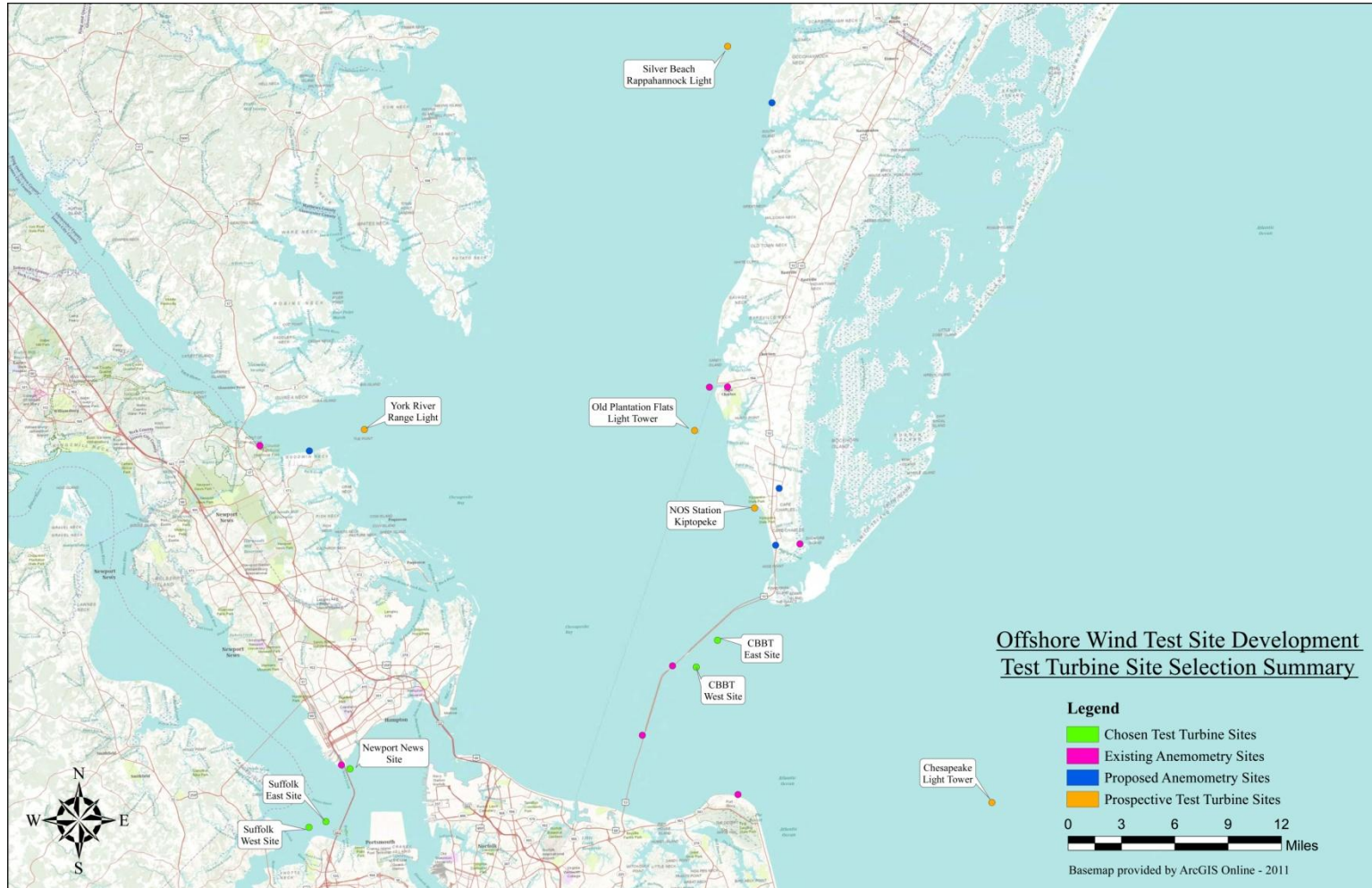


Figure 6: Offshore Wind Test Site Development Site Selection Map
Source: Timmons Group

“Virginia Offshore Wind Advanced Technology Demonstration Site Development” Project Work Scope

There are six primary tasks involved in this effort. Task One has JMU, through the Virginia Center for Wind Energy (VCWE), charged with introducing and managing communications with key stakeholders, elected officials, and relevant government agencies to gather input and gauge support, as well as identifying potential regulatory and micro-siting project constraints. The VCWE was also responsible for overall project management and coordination of efforts, and managing deliverables. This included gathering and compiling information into a final report, and creating a web portal to disseminate that information online with the public and other interested parties.

Task Two, sub-contracted out to the engineering firm, Timmons Group of Richmond, Virginia, involved a majority of the site analysis and concept development efforts. This included creating a detailed site location map using GIS data, to be incorporated into the project website through a mapping component it would design and build with JMU. Timmons Group was tasked with preparing a Geosciences Desktop Study (GDS) to analyze seafloor and subsurface characteristics and to identify exclusion areas within the proposed site locations. Interconnection options and a turbine concept plan were also developed. Additionally, Timmons Group prepared a preliminary engineering report including a corridor study to identify the least invasive route for the main power cables at each site.

Timmons Group also assumed the lead in preparing the proposed projects for the regulatory permitting process in Task Three by researching and compiling the required documentation to facilitate future permit acquisition. This included various federal permit

requirements, state and federal environmental impact reports, and local government zoning and land use permits.

Split into three phases, Task Four included the bulk of metocean resource characterization. WeatherFlow, the sub-contractor for Phase One, was tasked to develop and run for one year a numerical wind modeling system tailored to coastal and offshore Virginia. All output data will be included in a final report that will be compiled that summarizes overall analyses, as well as attempted and successful model changes following each of the eight annual sub-seasons to improve performance. In Phase Two, the Old Dominion University Center for Coastal Physical Oceanography (ODU-CCPO) was responsible for obtaining historical measured datasets from selected stations in Virginia to determine long-term (10-year) wind speed probability distributions and wind direction roses, as well as extreme wind speeds to determine low-wind duration probabilities and extreme water levels to determine the depth-limited breaking wave height at each of the three proposed sites.

VCWE supplemented ODU-CCPO's analyses in Phase Three with the deployment of a 50-meter meteorological tower at a site in Suffolk city, as well as the development of two annual energy production (AEP) models, one for the two inland sites and the other for the CBBT site. The VCWE applied WindFarmer's Measure-Correlate-Predict (MCP) module to integrate historical WeatherFlow and VCWE meteorological data from the surrounding areas and to interpolate wind statistics at the proposed project sites. This information, along with contour and roughness maps created using Global Mapper software from elevation and terrain data, was used to create a wind resource grid,

at particular heights, with WAsP software. WindFarmer was used to apply the wind resource grid to generate an AEP model for a hypothetical turbine at each location.

Principle Advantage Ltd., a consulting and lobbying firm out of Hampton Roads, led Task Five to engage in outreach to critical stakeholders from industry, environmental groups, and key government agencies. This task focused on engagement with stakeholder groups that are likely to be directly affected by or involved in the development and operation of the test pad sites.

The VCWE maintained responsibility for tackling the issue of aesthetic impact and visibility in Task Six for each of the turbine test pad sites. Visual simulations were produced to demonstrate the appearance of an appropriately sized turbine from a number of critical vantage points surrounding each site.

Conclusions

Identifying and understanding the unique challenges that have hindered U.S. offshore wind development begins with first recognizing the extent of European progress, because it demonstrates that the technology and expertise do exist to successfully advance an offshore industry. This, together with the demonstrated wind resource potential and favorable conditions along the mid-Atlantic, Great Lakes, and Gulf coastlines, indicates the potential of developing offshore wind markets in the U.S. However, a number of critical barriers exist that must be overcome before the U.S. can begin to take advantage of this vast, renewable resource. Efforts such as the “Virginia Offshore Wind Advanced Technology Demonstration Site Development” project are helping to address uncertainty and reliability issues related to infrastructure and resource characterization as well as to attract and jumpstart industry development.

Phase One

Chapter Three – Introduction to Meteorology, SST, and Wind Modeling

Introduction

Phase One addresses the immediate need to improve the reliability of metocean data as it pertains to characterizing the offshore wind resource at distinct locations. To demonstrate the importance of sea surface/atmospheric interactions in weather prediction and wind modeling, a basic overview of some of the meteorological concepts that influence coastal wind processes has been provided, as well as an introduction to atmospheric modeling systems and how sea surface temperature plays a role in numerical weather prediction.

Meteorology and Weather Basics

Meteorology is a subdivision of atmospheric sciences that constitutes the scientific study of all changes in the Earth's atmosphere, and is particularly useful in weather forecasting (MetEd, 2008). Weather, generally in the form of day-to-day temperature, wind, and precipitation activity in a given area, describes an endless cycle of events that together constitute the state of the atmosphere (MetEd, 2008). Over long periods of time, these meteorological cycles average into measures of climate, or long-term weather patterns, over a particular region. Weather phenomena, including wind, clouds, rain, snow, fog, and dust storms, as well as natural disasters such as tornadoes and hurricanes, only occur within the troposphere, or bottom layer of the atmosphere in direct contact with the Earth's surface (MetEd, 2008).

The primary drivers for weather stem from the interactions of the earth's atmosphere with its land masses and oceans. This interaction is initiated by the sun, the rays of which filter through the atmosphere and are absorbed at the earth's surface. The energy absorbed is then released into the air as thermal energy, warming the air directly above the surface. This exchange of energy initiates upward air movement because warm air rises, often carrying with it water vapor (DocWeather, 2012). As the warm air moves away from the Earth's surface it cools, and eventually sinks, causing the formation of clouds as the water vapor condenses into physical water droplets (DocWeather, 2012). An illustration of this phenomenon, called the convective cycle, is depicted in Figure 7 below.

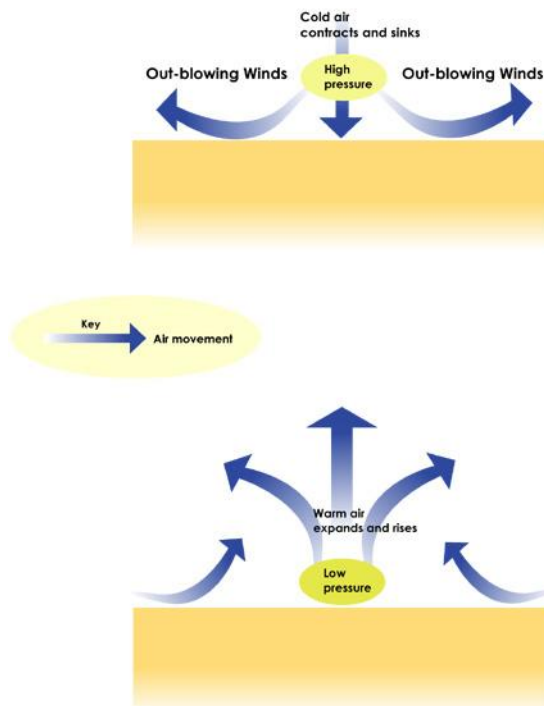


Figure 7: Illustration of the Convective Cycle to Determine Air Pressure Differences
 Source: <http://library.thinkquest.org/C0112425/image/children/airp.jpg>

In addition, different regions of the Earth are heated at different rates, and at night those regions also cool unevenly. This effect is primarily related to the angle at which sunlight strikes the earth, which depends both upon the earth's orbit around the sun as well the rotation about its own tilted axis (MetEd, 2008). All this unequal diurnal heating and cooling creates differences in atmospheric pressure, which causes the formation of high and low pressure systems (NCAR, 2012). Air from regions of high pressure flows naturally toward regions of low pressure, and this movement of air is called wind (NCAR, 2012).

The wind then interacts with another major force that influences weather, the oceans. The exchange of energy between the ocean and the atmosphere, combined with the rotation of the planet, causes the formation of prevailing winds and ocean currents. Easterlies and westerlies, prevailing winds which generally blow east-to-west or west-to-east, respectively, carve out underwater channels that drive the ocean's currents (NCAR, 2012). Warm water currents flow away from the equator along the eastern coasts of all continents, while cold water currents flow toward the equator along the western coasts of all continents (NCAR, 2012). These normal patterns of ocean currents, like the powerful Gulf Stream located off the east coast of the U.S. as shown in Figure 8 below, cause seasonal traits such as precipitation or mild climates, and also influence more extreme weather events such as hurricanes, intense storms where winds often exceed 119-km per hour (NCAR, 2012).

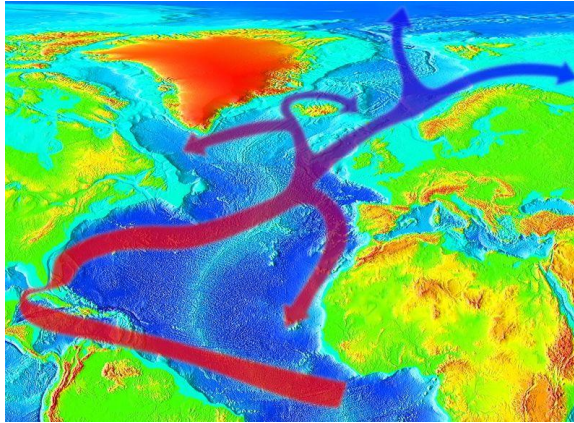


Figure 8: Gulf Stream Air Currents
 Source: <http://en.wikipedia.org/wiki/File:Gulfstream.jpg>

Weather phenomena that affect wind

Total Wind Resource

A conceptual understanding of the mesoscale weather phenomena that result from these dynamic interactions between the Earth's surface and its atmosphere is an important part of determining the total wind resource of a particular area. Wind profiles in coastal or the Great Lakes regions are particularly challenging to model because they exist within the marine boundary layer (MBL), which encompasses both over-land and over-water forecast areas. On an annual basis, the total wind resource of a region can be loosely represented by the following expression:

$$\text{Total Wind Resource} = f(\text{frontal passages} + \text{continental air intrusions} + \text{sea breezes} + \text{low-level jets} + \text{coastal lows} + \text{tropical intrusions} + \text{other wind sources})$$

This equation constitutes a majority of the coastal weather processes affecting winds within the MBL. Taken together, they help create an accurate description of the annual wind resource which, when modeled accurately by forecasting systems, provides key insight for wind developers regarding the potential wind energy available in an area of

interest. The following sections provide short introductions to some of these common phenomena.

Frontal Passages

One of the principal causes of meteorological phenomena are weather fronts. Generally referring to the boundary between two air masses of different densities, coastal fronts are mesoscale features that form in response to favorable geographic features such as those along the U.S. Atlantic coast. When a very cold, high-pressure air-mass originating in the north moves down the coast, the Appalachian Mountains to the west form a barrier preventing the air-mass from dissipating inland, and the warm Gulf Stream to the east provides the perfect setting for the formation of a coastal front (MetEd, 2001). As illustrated in Figure 9, the cold air interacts with the warm air above the Gulf Stream, creating a strong surface temperature gradient in the coastal region which is enhanced by cold air damming along the mountain range (Appel, et al., 2005). Not only are coastal fronts associated with persistent cloudiness and precipitation, but cold air on the landward side of the front typically remains close to the surface, making it particularly sensitive to surface-atmospheric heat exchange; all of which make coastal fronts difficult to depict accurately by regional atmospheric models (MetEd, 2001).



Figure 9: Illustration of Coastal Fronts Associated with Cold Air Damming and Gulf Stream Current on the Atlantic Coast

Source: http://www.nc-climate.ncsu.edu/climate/winter_wx/Patterns.php

Sea Breezes

Sea breezes, also called onshore breezes, are thermally-forced circulatory winds that develop in most coastal regions. Typically occurring on a diurnal cycle, sea breezes form from temperature gradients between land and sea surfaces (MetEd, 2002). Figure 10 shows that during daytime solar heating, the sea has a greater heat capacity than land and is therefore able to absorb more heat, causing its surface to heat up more slowly than on land. As the temperature of the surface of the land rises, the air above is heated and begins to rise, lowering the air pressure. Cold air advection (CAA) occurs as the cooler air over the water flows into the area of lower pressure, creating a cool onshore breeze near the coast (MetEd, 2002). The strength of a sea breeze is directly proportional to the temperature gradient across the coastal boundary (MetEd, 2002). As land cools in the evening more quickly than the sea surface temperature, this circulation diminishes and the process often reverses itself by forming, albeit weaker, land breezes at night.

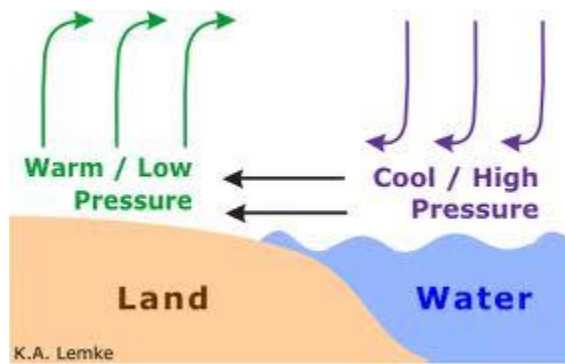


Figure 10: Illustration of the Formation of Sea Breezes
 Source: <http://www.biothermenergy.com/index.php?page=wind-energy>

Low-Level Coastal Jets

In contrast to sea and land breeze circulation, low-level coastal jets occur when only the land, not the sea, warms and cools according to a diurnal cycle. Due to cold water currents and upwelling events, the sea surface temperature remains cooler than the land throughout the day, which keeps air temperatures cooler in the MBL and prevents strong offshore winds (MetEd, 2004). This creates a strong pressure gradient between the land and sea surfaces, reaching a maximum along the coastline, which causes the low-level wind to increase and leads to a coastal jet (MetEd, 2004). Topographic influences such as mountainous coastal terrain keep the coastal jet flowing parallel to the coast; Figure 11 illustrates this effect. Forecasting of low-level coastal jets involves careful monitoring of surface pressure gradients along the coast, and with sufficient resolution, can generally be modeled quite accurately (MetEd, 2004).



Figure 11: Low Level Jet Formation

Source:

https://www.meted.ucar.edu/training_module.php?currentPage=showAll&id=153

Synoptic Weather Typing and Atlantic Coast Sub-Seasons

Understanding the way nature produces weather is a critical factor for forecasting, but just as important is accurately capturing the climatological make-up of an area of interest through synoptic weather-typing. This strategy provides a classification system that categorizes weather events occurring in a region by the time of the year during which they typically take place. Often, certain mesoscale and synoptic-scale weather events in a particular area, such as along the eastern coast of the U.S., have been found to be more prevalent during certain periods of the year. This can be applied to the wind resource equation described previously, which can be expanded from one annual average equation to incorporate individual equations tailored to each particular sub-season. Development of these sub-season-specific wind resource equations allows for the elimination of certain weather variables during sub-seasons in which they rarely occur or do not contribute heavily, which helps to generate a more accurate, in-depth description of the annual wind resource in a region of interest. The dominant weather events that reflect the climatology of the mid-Atlantic coastal region can be broken down into eight annual sub-seasons, as depicted by WeatherFlow in Table 1 below. In this table, each 45-day period is

characterized by different weather phenomena and wind drivers, some of which are more easily forecasted than others.

Table 1: Atlantic Coast Sub-Season Breakdown and Weather Characterization

Date	Sub - Season	Dominant Events
Jan 1 st to Feb 15 th	Mid – winter	CAA, Arctic Highs
Feb 16 th to Mar 31 st	Late Winter	Occas. tropical intrusions, cyclogenesis
April 1 st to May 15 th	Early Spring	Energetic warm and cold fronts
May 16 th to Jun 30 th	Late Spring	Dying fronts, max sea breeze season
Jul 1 st to Aug 15 th	Early Summer	Sea breezes, low-level coastal jets
Aug 16 th to Sep 30 th	Late Summer	Doldrums (low wind) with tropical intrusions
Oct 1 st to Nov 15 th	Autumn	Return of fronts with water still warm
Nov 16 th to Dec 31 st	Early Winter	Freq. fronts with CAA

Source: Jay Titlow, Senior Meteorologist, WeatherFlow

Atmospheric Models

Atmospheric models forecast weather conditions and climate using mathematical equations to represent the complex physics and dynamics of the atmosphere. First attempted in the early 1900s by Lewis Fry Richardson, the idea of translating the physical laws of the atmosphere into a complex set of mathematical equations was not successfully implemented until the 1950s, when modern computers simplified the computation process and began to allow for timely forecasts (Graham, et al). Over the years, more powerful computers have been used to incorporate larger datasets and more complex equations. The horizontal domain of an atmospheric model can be either global or regional; regional models cover a limited-area, but use smaller grid spacing, thus enabling them to resolve smaller-scale meteorological phenomena than global models.

Some of the better known regional mesoscale models include the Weather Research and Forecasting Model (WRF) and the Regional Atmospheric Modeling System (RAMS). WRF, the successor of an earlier version called MM5, was developed by

Pennsylvania State University and the National Center for Atmospheric Research (NCAR). The Nonhydrostatic Mesoscale Model (NMM) version of WRF is widely adopted, used by the National Oceanic and Atmospheric Administration's (NOAA) National Weather Service (NWS), the U.S. military, and other public and private organizations for forecasting and research (WRF, 2011). The concept for the RAMS was developed at Colorado State University's Department of Atmospheric Science in the 1980s (CSU, 2011). The first complete version, released in 1988, merged the capabilities of existing cloud and sea breeze models from the 1970s into a highly versatile numerical code (CSU, 2011). Development has continued over the years to incorporate advances in programming, computational speed, and complexity of the equations that support dynamic atmospheric modeling systems.

Introduction to RAMS and History of Development

RAMS, along with all other numerical weather prediction models (NWP), is composed of a set of fundamental equations that govern atmospheric motion, and offers a number of physical and numerical options for grid structure, dimensionality, condensation, radiation, boundary conditions, initialization, and other configuration features. Those fundamental equations are often supplemented with optional parameterizations. Parameterization is a procedure used to represent processes that are too small-scale or complex to be clearly defined in NWP models by relating them to variables consistent with the model's scale. Some optional parameterizations include turbulent diffusion, solar and terrestrial radiation, moisture process including the formation and interaction of clouds and precipitating liquid and ice hydrometeors, sensible and latent heat exchange between the atmosphere, multiple soil layers, a

vegetation canopy, surface water, the kinematic effects of terrain, and cumulus convection (CSU, 2011). This allows an individual model to be tailored to a particular meteorological regime, such as mountainous terrains, desert regions, or coastal zones. RAMS is considered a ‘limited-area model’ and uses two-way interactive grid nesting, which allows the depiction of larger-scale weather environments in the courser grids while simultaneously modeling micro-scale atmospheric phenomena in finer mesh grids (CSU, 2011).

WeatherFlow RAMS Coastal Zone Model

WeatherFlow runs an operational version of RAMS that provides high resolution modeling capabilities along a majority of U.S. coastlines. For the purposes of this project, a RAMS has been developed tailored to represent the unique characteristics of the mid-Atlantic coastline, in particular off North Carolina and Virginia. As illustrated by Figure 12 below, WRAMS utilizes three nested grids which provide model output at 24, 8, and 2-km resolutions.

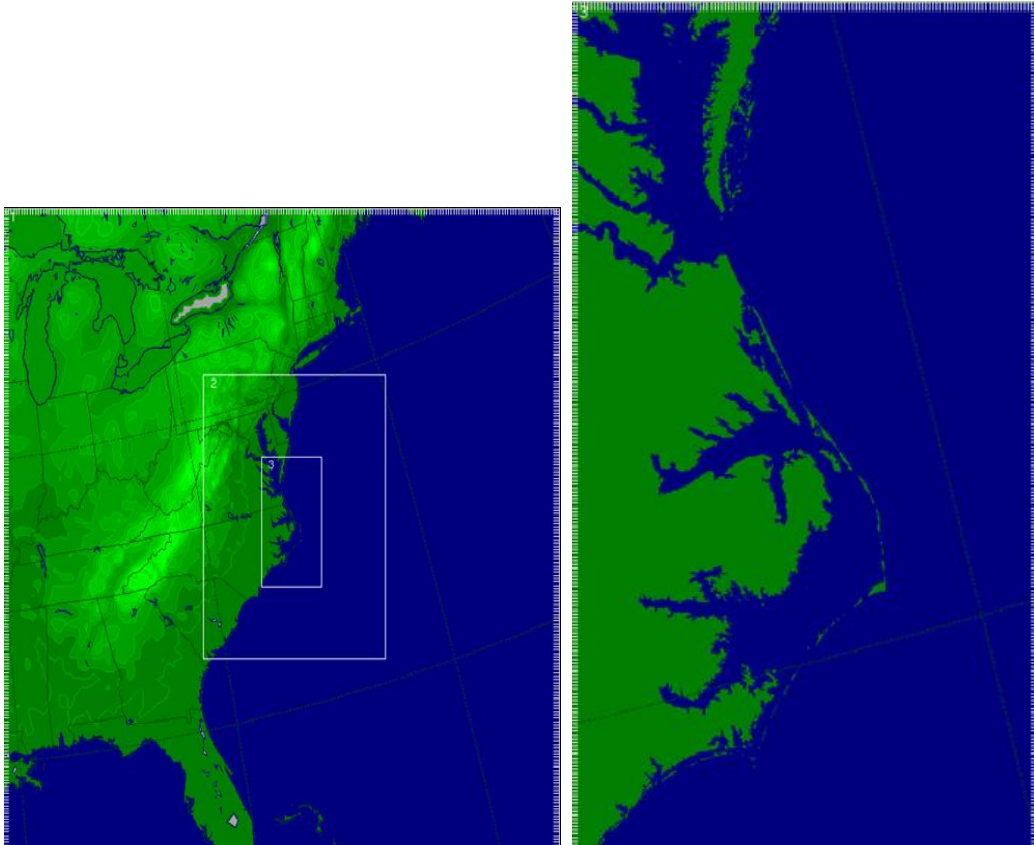


Figure 12: WeatherFlow RAMS Atlantic Coast Grid Spacing
Source: <http://stone.weatherflow.com/cgi-bin/scripts/forecast.cgi>

Influence of Sea Surface Temperature

Sea surface temperature (SST), land use, and topography are among the surface characteristic datasets used in WRAMS initialization procedures. Often difficult to define, SST is used to describe the exchange of energy between the ocean and the atmosphere. Subject to diurnal changes, and affected by ocean currents as well as on- and offshore winds near shore, SST interacts with and can significantly affect air masses in the atmosphere above the water surface. For example, strong offshore winds can cause coastal upwelling, a process which transports water from deeper layers of the ocean closer to the surface (Tomczak, 1996). This denser, cooler water is responsible for major

coastal nutrient regeneration and, depending on water depth and topographic detail, can significantly alter the SST along coastlines (Tomczak, 1996). Changes in SST can also cause the formation of sea breezes and influence other air-sea interactions, all of which must be taken into account by NWP models to accurately forecast atmospheric conditions.

The SST data used in WRAMS is provided by NASA through the Group for High Resolution Sea Surface Temperature (GHRSSST). GHRSSST is a collaborative, international project that processes and analyzes data streams from all over the world to provide access to high resolution SST data (GHRSSST, 2011). This group oversees the input, processing, analysis, documentation, and output of SST data streams, managing and integrating them together to create high resolution SST data sets with global coverage that can be shared internationally across a wide variety of applications (see Figure 13 for example). In general, SST describes the top layer of the ocean or other large bodies of water, but is a difficult parameter to describe because the top 10 m of the ocean have a complex vertical temperature structure. Dominant influences from air-sea interactions such as surface heat, moisture, momentum, and freshwater fluxes are the main processes that determine ocean-atmosphere boundary layers and help define this vertical temperature structure (Soloviev & Lukas, 2006).

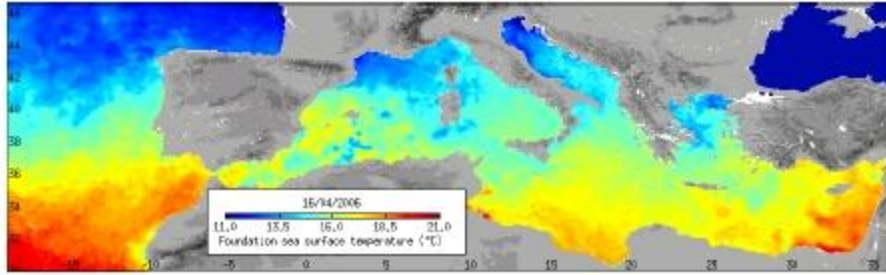


Figure 13: An Example of the Global Coverage Foundation SST provided by GHRSSST
Source: <https://www.ghrsst.org/data/data-descriptions/14-gridded-sst/>

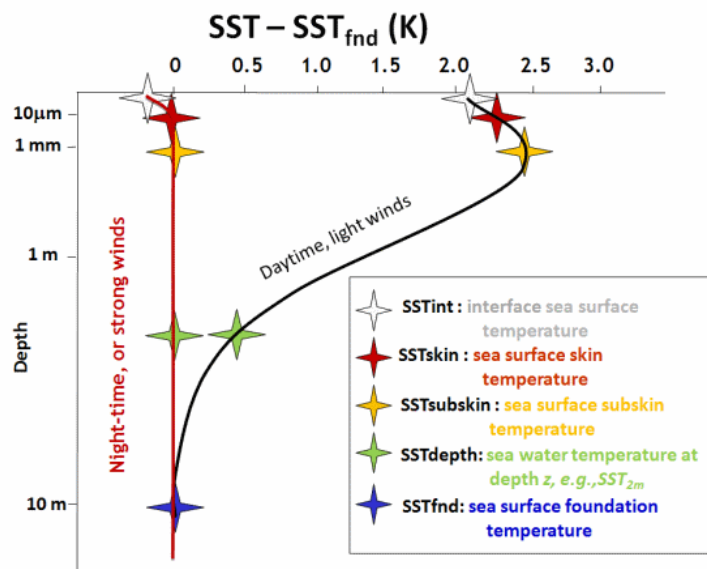


Figure 14: Vertical Profile of SST in Upper Ocean Layer
Source: <https://www.ghrsst.org/ghrsst-science/sst-definitions/>

GHRSSST has created a theoretical framework that describes the relationships between the multiple types of SST that exist in the surface layer and how they can each be measured. Figure 14 summarizes these types in a hypothetical vertical profile; one depicts SST during high surface wind speeds or nighttime conditions (red line), and the other low surface wind speeds or daytime conditions (black line). A large diurnal variability exists between the two hypothetical SST profiles, creating a disparity between SST values closest to the surface during day and night conditions. Influences from wind

conditions and other atmospheric phenomena also contribute to this difference near the surface. The interface temperature (SST_{int}) is the hypothetical temperature at the exact air-sea interface, and although defined, the SST_{int} cannot currently be measured with existing technology (GHRSSST, 2008). The skin sea surface temperature (SST_{skin}) is located between 10 and 20 μm below the SST_{int} and can be measured by an infrared radiometer (GHRSSST, 2008). The SST_{skin} and the sub-skin sea surface temperature ($SST_{subskin}$) are within the convective sub-layer of the ocean surface dominated heavily by diurnal fluctuations and wind conditions. The $SST_{subskin}$ is at the base of this sublayer (approximately 1 mm below the air-sea interface), and can be well approximated by indirect measurements from a microwave radiometer (GHRSSST, 2008). All measurements of water temperature below the $SST_{subskin}$ are referred to as depth temperatures (SST_{depth}), which can be measured in-situ using a variety of physical sensors such as buoys or deep thermistor chains rather than remote sensing technologies (GHRSSST, 2008).

Perhaps the most important SST for this application, the sea surface foundation temperature (SST_{fnd}), is found below the diurnal thermocline. Generally, at depths at or below 10 m, diurnal influences diminish and the two SST profiles in Figure 14 converge. Officially defined as ‘the temperature at the first time of the day when the heat gain from the solar radiation absorption exceeds the heat loss at the sea surface,’ SST values at all depths typically collapse to the SST_{fnd} just before sunrise, at which point influences from daily solar radiation/heating are minimal (GHRSSST, 2008). This effect is illustrated in the Arabian Sea WHOI Mooring Data from spring 1995 shown in Figure 15 below. The SST_{fnd} is important because it is considered the base temperature upon which diurnal

heating and cooling occurs each day, and is the SST value utilized by WeatherFlow as a RAMS input variable. Only physical measurements can truly determine SST_{fnd}, but remotely-sensed SST_{skin} and SST_{subskin} values taken at other times in the day can be used to estimate the SST_{fnd}. To achieve this, GHRSSST analyzes and integrates data streams from both in situ and remotely-sensed SST measurements to interpolate SST_{fnd} values, and generate accurate, high resolution global SST_{fnd} data that WeatherFlow can utilize.

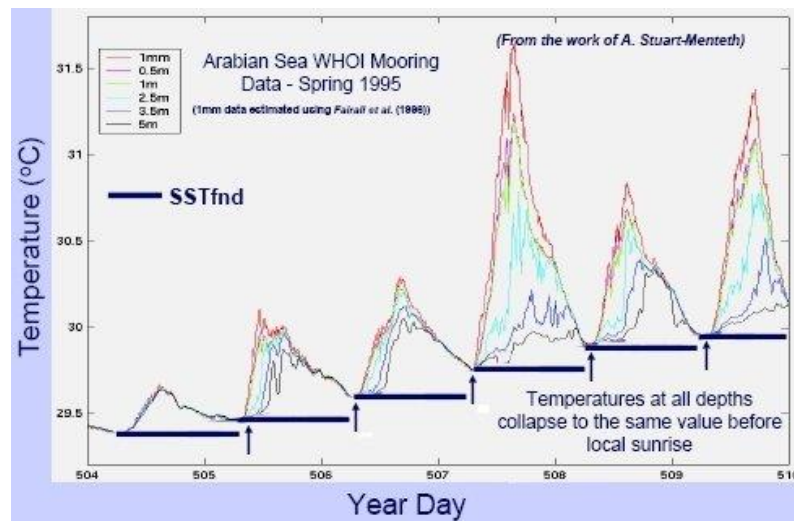


Figure 15: Example of SST_{fnd} in Arabian Sea WHOI Mooring Data – Spring 1995
Source: <https://www.ghrsst.org/ghrsst-science/sst-definitions/>

Wind Resource Deliverables with the ‘Offshore Wind Test Site Development Effort’

Within the scope of the “Offshore Wind Test Site Development Effort” project, WeatherFlow’s wind resource assessment work aims to accurately model the wind resource in and around the sites of interest off the coast of Virginia, near-shore at either end of the Monitor Merrimac Bridge Tunnel and further offshore near the Chesapeake

Bay Bridge Tunnel. Specifically, WeatherFlow has been tasked with constructing and running a numerical wind modeling system (WRAMS) with a horizontal grid resolution down to 2-km for one year, during which time daily meteorological and model analyses have been performed to assess model performance. A review of events at the end of each of the eight annual sub-seasons, comparing meteorological categorization with model skill score, will help identify and attempt to correct possible causes for low performance. While the original operational model will continue to run for the year as a control, model changes accumulated from each sub-season to date have been developed and implemented, running parallel to the original as well as performing various hindcast runs for periods of interest.

Introduction to Hypothesis and Methodology for Testing

In its operational model, WeatherFlow currently utilizes 9-km resolution SST data acquired through NASA from GHRSSST as one of many surface characteristic inputs for each model run. This SST data can only provide a limited resolution of SST characteristics at land-sea boundaries, which is of particular importance for the sites analyzed in this application due to their proximity to shore. Recently, higher resolution 1-km SST datasets have become available, and WeatherFlow has hypothesized they will be able to more accurately describe coastline SST conditions than the 9-km datasets, and that incorporating these higher resolution datasets will improve WRAMS forecasting accuracy.

The first step in determining the usefulness of higher resolution SST data has involved an evaluation of how the 1-km and 9-km SST data compare to observational values gathered in situ from WeatherFlow's numerous weather stations and buoys within

the area of interest. The work in this dissertation specifically evaluates the accuracy of these data within one of the eight annual sub-seasons, the ‘early winter’ period from mid-November through the end of December, 2011. Although this limited analysis encompasses only a fraction of the period under investigation, and comparisons of additional sub-seasons may provide more comprehensive results and additional insight, it gives an initial indication of the accuracy relative to the use of the 1-km SST dataset.

In response to this initial analysis, an updated version of WRAMS has been developed by WeatherFlow that utilizes the 1-km SST data, and has since been running operationally alongside the original model. In addition to evaluating the original and updated models’ forecast accuracy against real-time observations throughout the year, additional model adjustments correcting observed time lag in the 1-km data have been tested through model re-run analyses for short time periods of particular interest. Building upon the initial, single sub-season SST accuracy assessment, an additional comparison of SST performance in these test cases has been carried out to further examine the hypothesis defined within this dissertation. Finally, meteorological verification statistics were compared for the forecasts and hindcast model re-run test cases to assess the influence of more accurate SST inputs in model performance, and to determine the overall value of moving to the higher resolution SST datasets.

Chapter Four – Presentation of Results and Analyses

Description of Meteorological Stations and Introduction to Data Used

The first phase of SST analysis involves a comparison of 1-km and 9-km SST data with observational values gathered during the ‘early winter’ sub-season from mid-November through the end of December. Both the 1-km and 9-km data, derived from GHRSSST, are once-daily values, and include short periods where no data were received. The observational values were collected from measurements at a number of meteorological stations near the test-pad sites of interest in the “Virginia Offshore Wind Advanced Technology Demonstration Site Development” project and the number of measurements taken each day varies between stations. For the purposes of this analysis, daily averages were calculated for the measured SST values at each site to simplify the comparison process over the sub-season.

The sites identified for analysis include three sites off the Virginia coast, the ‘first island’ on the northeast side of the Chesapeake Bay Bridge Tunnel, Kiptopeke State Park, and the Yorktown Coast Guard Training Center, as well as a Virginia Beach buoy, located approximately 64 nautical miles offshore. Data from three North Carolina sites, including Avon Sound, Duck Pier, and Hatteras Island Ferry Terminal, were also utilized. Each station, as well as the location of the test-pad sites, can be viewed in Figure 16.

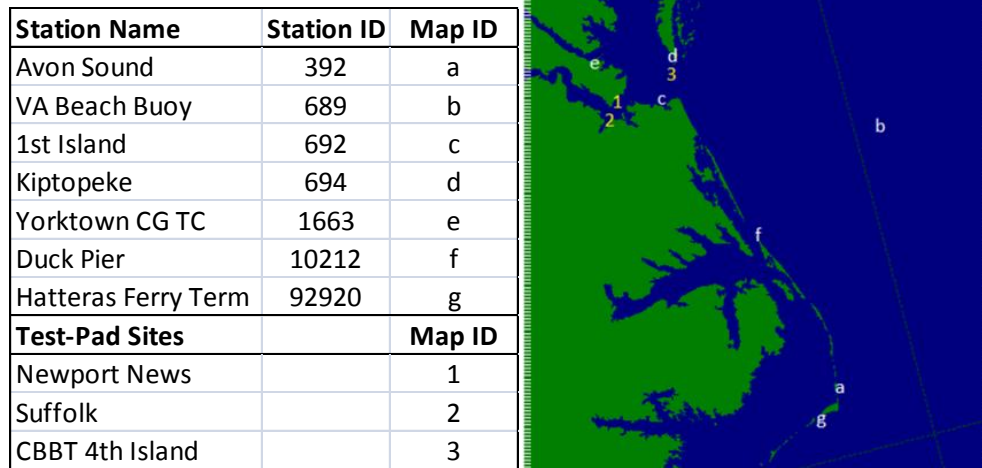


Figure 16: Map of Virginia and North Carolina Coastal Areas and Federal Waters, With Location of Proposed Test-Pad Sites and Stations used in Analyses

Mean Absolute Error Analysis

This initial analysis compared the performance of the 1-km and 9-km data over the 45-day, ‘early winter’ sub-season to observational values gathered in situ from the seven stations’ recorded SST measurements. Mean absolute error (MAE) was then used to compare the accuracy of each dataset against the observed SST measurements, which measures the absolute values of the differences between forecast and corresponding observations. It averages the magnitude of the errors without considering direction, which simplifies the process of comparing multiple locations. The equation for MAE is described below, where the mean error is the average of the sum of the errors. .

$$\text{MAE} = \frac{1}{n} \sum_{i=1}^n |f_i - y_i| = \frac{1}{n} \sum_{i=1}^n |e_i|.$$

$e_i = |f_i - y_i|$ where f_i is the 1-km or 9-km value and y_i the observed value.

Individual Station Results

The graphs in Figure 17 below describe the performance of the 1-km and 9-km SST data against the observed values collected at Station 392, Avon Sound, first in Graph (a) with the raw data in degrees Celsius, then in Graph (b) with the MAE values of the modeled SST data, also in degrees Celsius. Graph (a) shows significant deviation from observational values in both the 1-km and 9-km modeled SST data. The 9-km data appear to only slightly capture the overall trend of the observational values, and fail to demonstrate the range of temperature, ie. neither the highs nor lows are adequately represented. The 1-km data also appear to only give a representation of the overall trend of observational values, but they do a better job of attempting to capture some of the higher observational SST measurements toward the beginning and ending weeks of the sub-season. The peaks and troughs in the observational SSTs are also better represented with the 1-km data, although typically multiple degrees ‘off’ and with a time lag of a few days. According to the MAE analysis depicted in Graph (b) of Figure 17, the 9-km data performed slightly better, averaging a 1.9 degree difference from the measured values over the sub-season, while the 1-km data averaged an error of 2.0 degrees. Greatest error days occurred on December 14 for the 9-km data (5.0 degrees) and December 20 for the 1-km data (5.9 degrees).

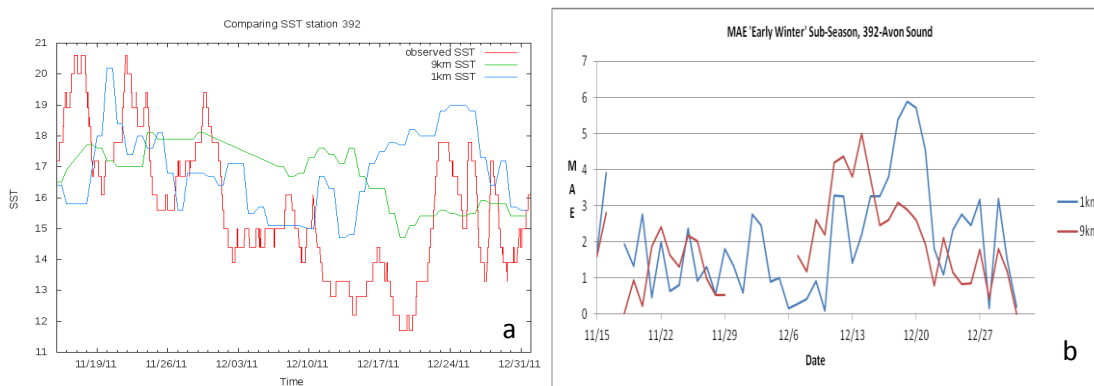


Figure 17: SST Analysis for Station 392 - Avon Sound, Nov 15-Dec 31
 (a) SST value comparison
 (b) MAE analysis

Graph (a) in Figure 18 below display the 1-km and 9-km SST data streams for Station 689, Virginia Beach Buoy. They more effectively represent the trend of the observational data than at the Avon Sound station, especially in December. Both modeled data streams, although the 1-km data gives a better attempt, have difficulty capturing the variability in temperature for the first two weeks of analysis. As shown in Graph (b) of Figure 18 below, the analysis using the 1-km data performed slightly better than that with the 9-km data, with MAE values for the sub-season averaging 0.73 degrees for the 9-km data and 0.72 degrees for the 1-km data. Maximum errors of 2.3 degrees for both data streams occurred within one day of each other, during the last few days of December.

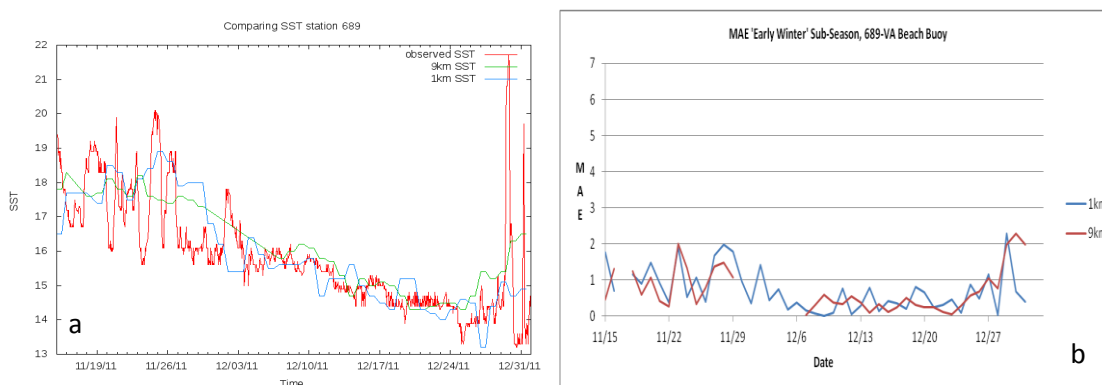


Figure 18: SST Analysis for Station 689 – Virginia Beach Buoy, Nov 15-Dec 31
 (a) SST value comparison
 (b) MAE analysis

As shown in Graph (a) of Figure 19 below, Station 692, at the Chesapeake Bay Bridge Tunnel ‘first island,’ shows the most accurate 1-km and 9-km SST data for all stations when compared with observational values over the length of the sub-season. Both modeled data streams offer an accurate representation of the general trend of the measured SST, with MAE values, displayed in Graph (b) of Figure 19 below, of 0.58 degrees for the 1-km data and 0.55 degrees for the 9-km data. Although these MAEs would suggest that, on average, the 9-km data are closer in value to the observed SST, Graph (a) in Figure 19 shows that the analysis with 1-km data describes many of the peaks and troughs in the measured SST data missed by analysis driven by the 9-km data throughout the sub-season. However, there appears to be a time lag, or phase offset, in the 1-km data of approximately 1 to 3 days behind the observed values. The multiple oscillations present within the observational SST values over the sub-season (approximately one per week), together with the time lag in the 1-km data, causes the appearance of troughs in the 1-km data when there are actual peaks in the observational data, and vice versa. This may account for the higher MAE value.

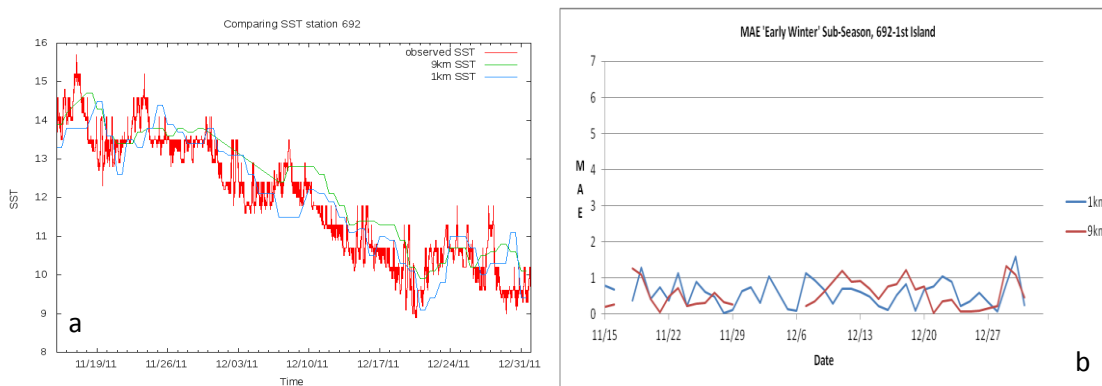


Figure 19: SST Analysis for Station 692 – CBBT ‘first island,’ Nov 15-Dec 31
 (a) SST value comparison
 (b) MAE analysis

Both the graph displaying raw SST data and the MAE analysis in Figure 20 below show that the 1-km and 9-km data streams for Station 694, Kiptopeke State Park, provide an adequate representation of the average trend of the observed SST through the ‘early winter’ sub-season. Similar to the stations already analyzed, the 9-km data demonstrate a slightly lower MAE value at 0.72 degrees as compared to the 0.68 degree average error for the 1-km data; and although depicting more of the peaks and troughs present in the measured values, the 1-km data lags behind by a few days.

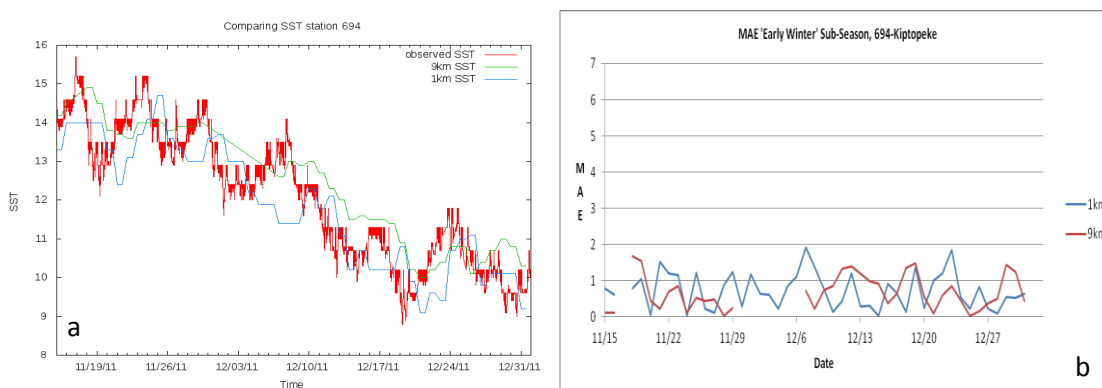


Figure 20: SST Analysis for Station 694 – Kiptopeke State Park, Nov 15-Dec 31
 (a) SST value comparison
 (b) MAE analysis

Located in an inland waterway within the Chesapeake Bay, meteorological Station 1663 at the Yorktown Coast Guard Training Center displays unique measurements for observed SST values over the ‘early winter’ sub-season. Due to the multiple measurements taken throughout each day at this location (every six minutes), the observed values fluctuate extensively and offer an excellent representation of the diurnal variability that exists for SST, especially at such an inland location. Graph (a) of Figure 21 below shows the 1-km and 9-km data, which display only one SST value per day, cannot capture diurnal variability, but appear to present a good representation of the ‘daily highs’ experienced in the observed values. In this case, MAE analysis compared the 1-km and 9-km data to an average of all the observed values that were measured over the period of each day. This amounted to an average of over 200 measurements with diurnal temperature fluctuations of approximately 3 degrees per day. MAE, displayed in Graph (b) of Figure 21, averaged 1.6 degrees for the 1-km data and 1.2 degrees for the 9-km, with maximums of 3.8 and 2.9 degrees, respectively, both occurring on November 19. These calculations suggest that, for this station, the 9-km data offer a better average estimation of real SST than the higher resolution data.

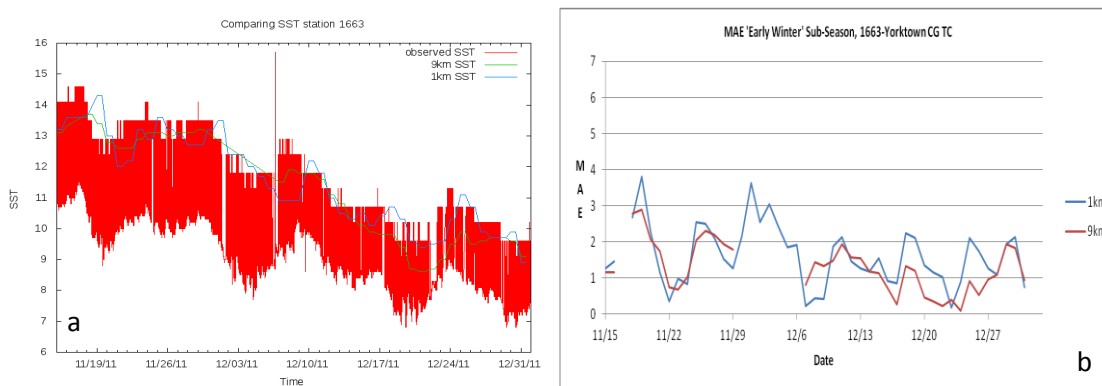


Figure 21: SST Analysis for Station 1663 – Yorktown Coast Guard Training Center
Nov 15-Dec 31
(a) SST value comparison
(b) MAE analysis

Over the length of the ‘early winter’ sub-season, observed SST values from Station 10212, Duck Pier, range between approximately 10 and 17 degrees Celsius, with maximum values occurring at the beginning of the sub-season and reaching the lowest values around December 18. Graph (a) in Figure 22 show that both the 1-km and 9-km data streams provide a good representation of the average trend of the observed SST values, but similar to previously analyzed stations, the 1-km data appear to lag behind by a few days. This may account for the higher MAE seen in Graph (b) of Figure 22 for the 1-km data; MAE values were 0.85 and 0.82 for the 1-km and 9-km data, respectively.

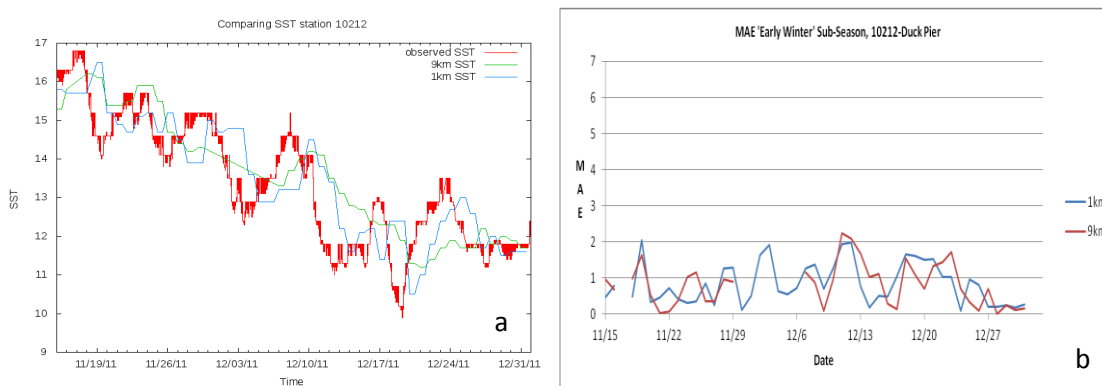


Figure 22: SST Analysis for Station 10212 – Duck Pier, Nov 15-Dec 31
 (a) SST value comparison
 (b) MAE analysis

The final dataset analyzed originated from Station 92920, at the Hatteras Island Ferry Terminal. Analysis with both 1-km and 9-km data, displayed in Figure 23 below, presented extreme difficulty depicting the trend of measured SST values, with MAE values of 3.0 and 2.8 degrees, respectively. Both modeled data streams failed to represent the variability of the observed values over the sub-season, generally predicting higher values than were experienced. At points of maximum error, which occurred in the middle of December, the modeled data were off by nearly 7 degrees Celsius. As demonstrated by the data from the previous stations, the MAE values suggest that the 1-km data performed more poorly than for the lower resolution data.

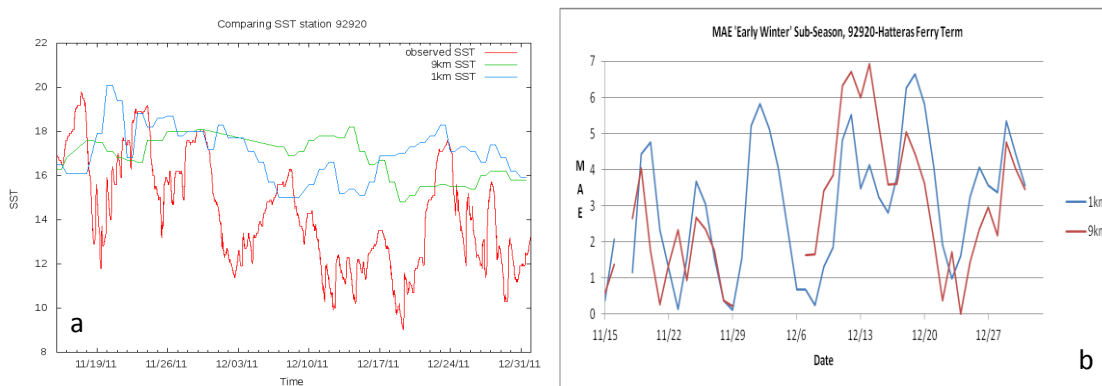


Figure 23: SST Analysis for Station 92920 – Hatteras Island Ferry Terminal
Nov 15-Dec 31

- (a) SST value comparison
(b) MAE analysis

Compilations of all MAE values over the length of the sub-season are displayed in Figures 24 and 25 for the 1-km and 9-km data respectively, allowing for a rough comparison of all the stations. Error for a majority of the stations generally fluctuated between 0 and 2 degrees Celsius, while Station 392, Avon Pier, and Station 92920, Hatteras Island Ferry Terminal, stand out as experiencing a large number of higher error days in both the 1-km and 9-km data. The 1-km MAE comparison in Figure 24 also demonstrate that in addition to Stations 392 and 92920, Station 1663, Yorktown Coast Guard Training Center, displays higher differences from the observed values during the first few weeks of the sub-season than the other stations.

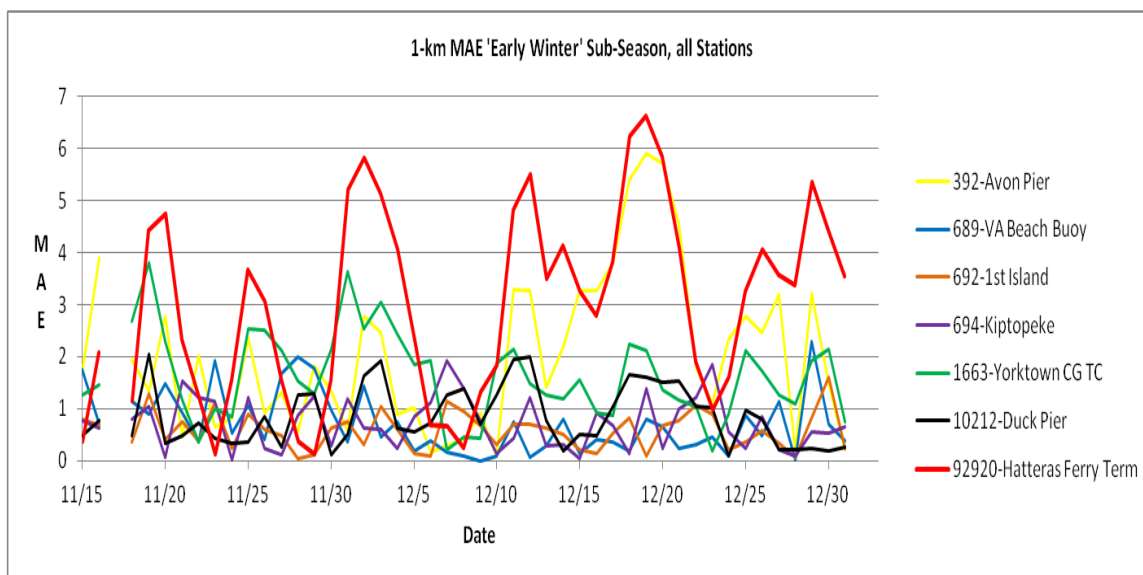


Figure 24: 1-km SST MAE Error For all Stations, Nov 15-Dec 31, 2011

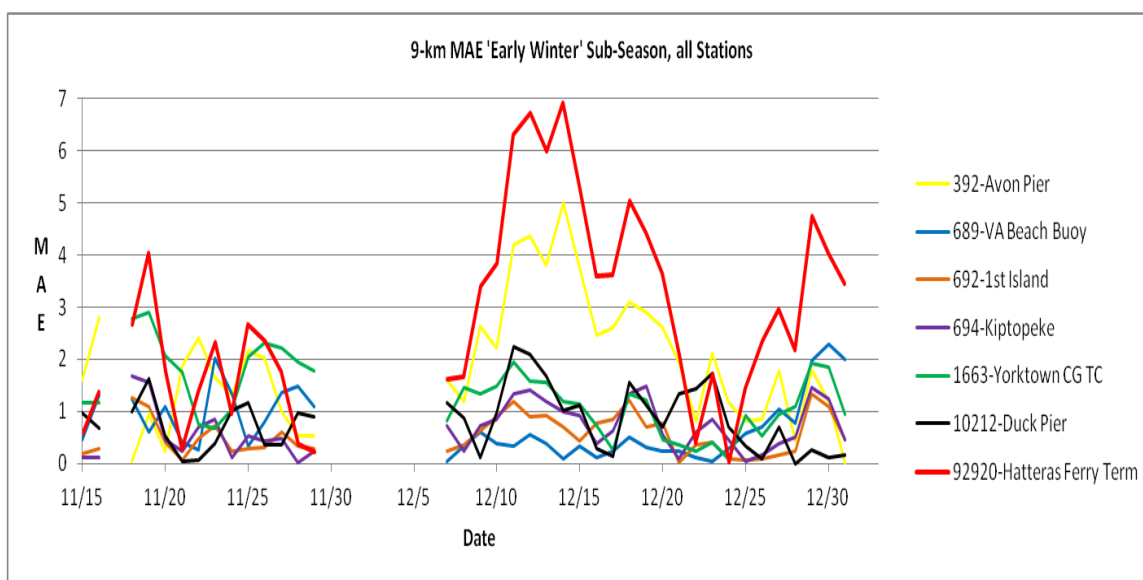


Figure 25: 9-km SST MAE Error For all Stations, Nov 15-Dec 31, 2011

Summary of Initial Analyses and Implications

In addition to comparing the performance between stations, Graph (a) in Figure 26 below displays the average 1-km and 9-km MAE values for all stations together in a bar graph to allow a comparison of the combined error associated with the different resolutions. For nearly every station, the 9-km data, averaged over the sub-season, experience less difference from the measured SST values.

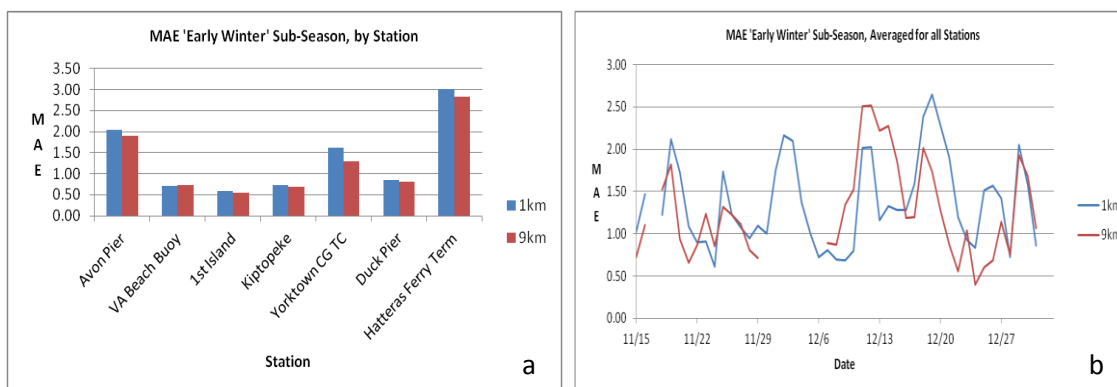


Figure 26: Compilation of Average MAE Values for all Stations, Nov 15-Dec 31

(a) Bar chart displaying average MAE values for 1-km and 9-km data at all stations

(b) Graph of 1-km and 9-km MAE values, averaging all stations together

Although there may be multiple explanations for the error among the different stations, Graph (b) in Figure 26 averages the MAE values from all the stations to give an indication of the overall regional accuracy, or lack thereof, for the different resolutions of modeled SST data. Considering the seven stations together, the overall average MAE for the 1-km data is 1.4 degrees, while only 1.3 degrees for the 9-km data. Although this limited sub-season data and analyses only demonstrate an average MAE increase of 0.1 degrees, these initial calculations suggest that the higher resolution data does not, in fact, offer a more accurate depiction of real SST within this region along the Mid-Atlantic coast.

Based upon this analysis alone, the hypothesis that 1-km resolution SST data would be able to more accurately resolve coastal sea surface characteristics would be rejected, and it would be determined that there is no benefit to WeatherFlow to shift from 9-km to 1-km resolution SST data in their RAMS initialization procedures. Not only does the 1-km data fail to significantly decrease the MAE, on average it actually performs worse than the 9-km data. These initial results are surprising, considering an intuitive assumption would lead one to associate increased accuracy with higher resolution data. For this reason, additional analysis has been made to attempt to explain these counterintuitive findings before officially rejecting the hypothesis, including determining correlation with wind vector error, discussing inherent error in SSTfnd estimation, and investigating the time lag experienced by the 1-km SST data.

Correlation with Wind Vector Error

Wind Vector Difference Error (WVD) is another statistical parameter used to determine model performance and forecast accuracy. Similar to the MAE, WVD represents the error in the model's projected wind vector (U and V components of wind) as compared to observed wind vector data measured from physical weather stations. This is a valuable statistical tool for determining error because it encompasses both the U and V components of the wind together. The following equation is used to determine WVD, where U_f represents the forecasted value for the U component, and U_o the observed U component. The same notation scheme is used for the V component.

$$WVD = \sqrt{\frac{1}{K} \sum ((u_f - u_o)^2 + (v_f - v_o)^2)}$$

If it can be determined that there exists a correlation between SST MAE values and WVD, which would suggest that days during which the 1-km or 9-km SST values

experienced high error were also particularly difficult for the model to forecast accurately, it may provide some explanation for unexpected degrees of error in the analysis using 1-km SST data that was seen in the initial MAE analysis.

Figure 27 compares mesoscale 1-km and 9-km MAE in SST data with mesoscale WVD values. Graphs (a) and (b) compare SST MAE and WVD values over the length of the sub-season for the 1-km and 9-km SST data, respectively, to determine if any obvious temporal correlation exists between the two error values. Neither graph offer any indication that SST and wind vector error are directly, or indirectly, related; there are days that display high/low SST and WVD error together, as well as days in which high error occurred for one variable but not for the other. Graphs (c) and (d) in Figure 27 expand on this analysis by directly comparing error values between the two variables. A linear relationship between the two variables, which was not experienced with the 1-km or the 9-km SST data, would have suggested some level of correlation and might have helped explain the 1-km SST error.

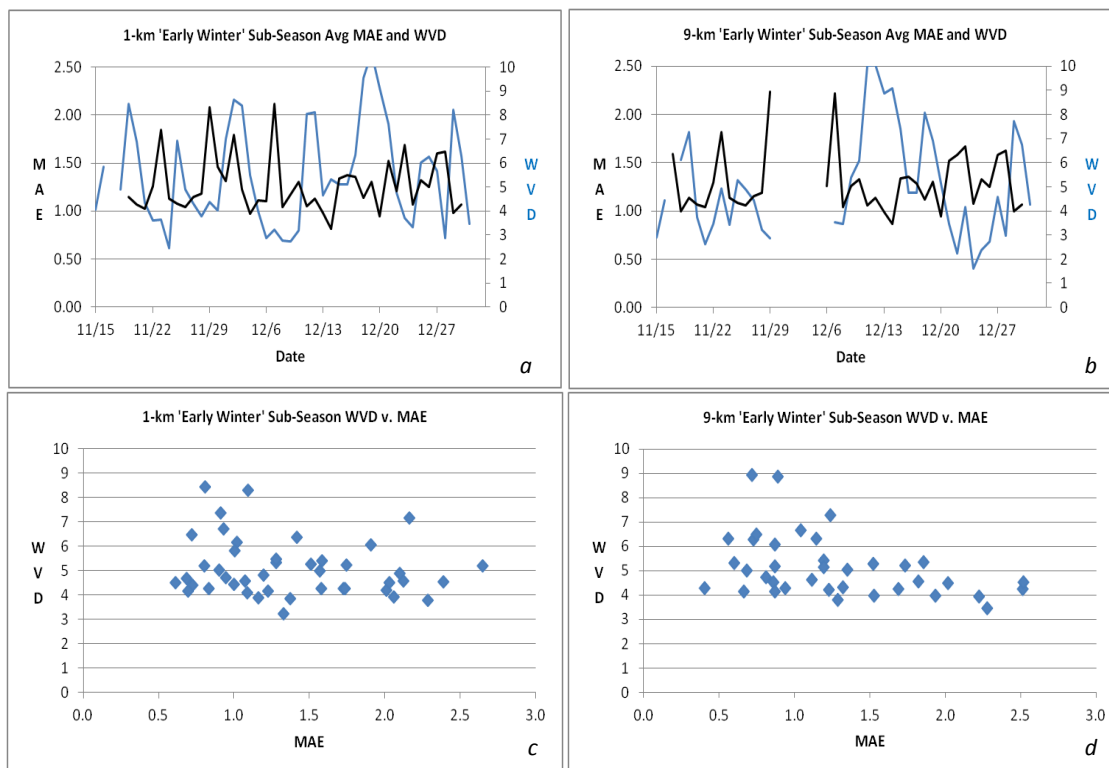


Figure 27: Comparison of averaged 1-km and 9-km MAE and WVD values
 (a) 1-km SST MAE and WVD comparison over length of sub-season
 (b) 9-km SST MAE and WVD comparison over length of sub-season
 (c) Correlation plot of 1-km MAE against WVD values
 (d) Correlation plot of 9-km MAE against WVD values

Referring back to Figure 17, three of the seven stations analyzed show similar characteristics; Station 692, on the ‘first island’ near the northern end of the Chesapeake Bay Bridge Tunnel, Station 694, near Kiptopeke State Park, and Station 1663, at the Yorktown Coast Guard Training Center. All three stations are located inside the Chesapeake Bay, relatively near to each other as well as to the three test-pad sites under review, and are all representative of difficult to resolve, inland waterways. In order to eliminate the possibility that the variability in the characteristics of the other four stations may have influenced the correlation analysis, it was repeated using only SST error associated with those three stations. Figure 28 displays the results of this analysis, which

do not demonstrate increased correlation between the variables at either resolution of SST data.

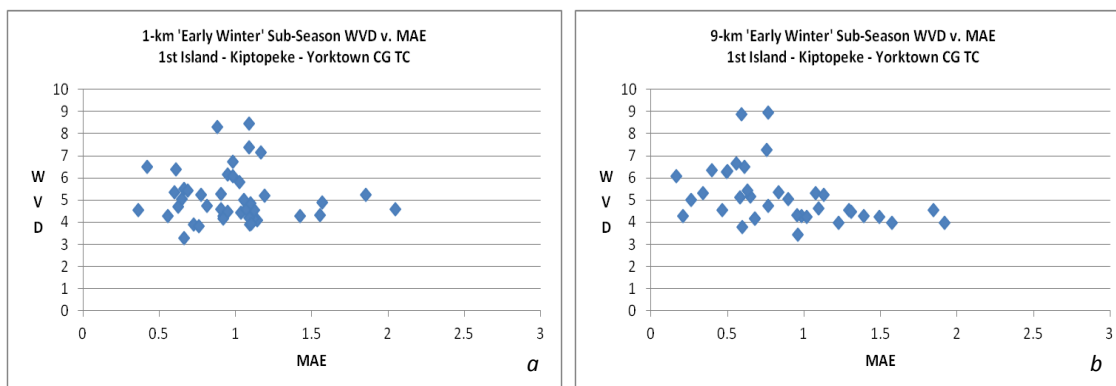


Figure 28: Comparison of adjusted average 1-km and 9-km MAE and WVD values (Stations 692, 694, and 1663 only)

- (a) Correlation plot of adjusted 1-km MAE against WVD values
- (b) Correlation plot of adjusted 9-km MAE against WVD values

Error Associated with GHRSSST Datasets

As explained in Chapter 3, WeatherFlow utilizes foundational SST, or the SST existing below the diurnal thermocline. These are compiled by GHRSSST, an international organization dedicated to providing high resolution, global SST coverage. Unlike SST types closer to the surface, SST_{fnd} cannot be measured using remote-sensing technologies such as infrared or microwave radiometers. Instead, it is approximated using measurable SST_{skin} and SST_{subskin} values, together with physically measured SST values at varying depths. Although impossible to confirm, it is worthwhile to mention the possibility of computational error associated with the interpolation process used to estimate SST_{fnd}. An unknown error inevitably affects in the accuracy and calibration of the instruments used. An increase of the resolution of an interpolated value could exacerbate an otherwise minute measurement error and cause higher resolution data to become less reliable than lower resolution data.

Latency Issues in the 1-km SST Data

Although the MAE analysis determined that, on average, the higher resolution data induces a higher level of error, a majority of the initial, station-specific graphs of observational SST values plotted against the 1-km and 9-km SST datasets show that the 1-km data appear to more accurately capture the variability (peaks and troughs) seen in the observed SST over the length of the sub-season. Most pronounced in Stations 692, 694, and 10212, the 1-km SST datasets often appear to lag behind the measured SST values by a period of 1 to 3 days. To demonstrate this, original observational SST data from Station 694 were adjusted ahead 48 hours, and Graph (b) in Figure 29 shows that this adjustment successfully corrects for the time lag in the 1-km SST product from GHRSSST. Error analysis using the time-adjusted data resulted in significantly reduced MAE values for SST data at both resolutions, from 0.72 to 0.44 degrees for the 1-km SST data, and from 0.68 to 0.47 degrees for the 9-km SST data.

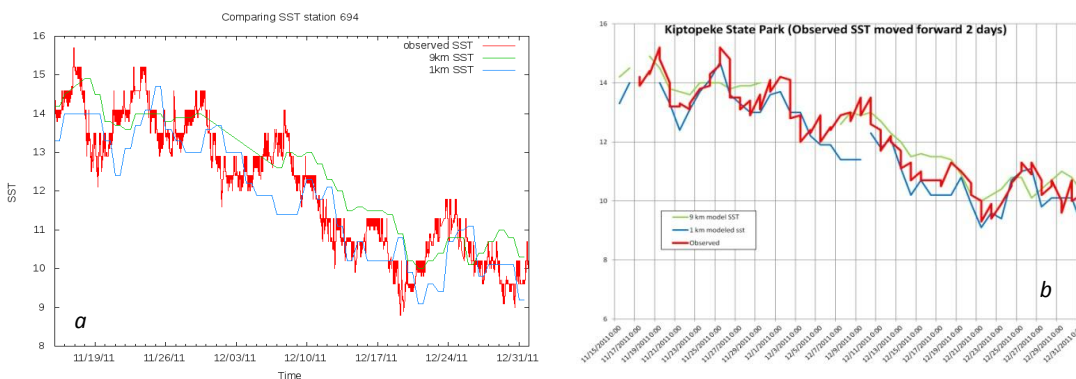


Figure 29: Comparison of Original and 'Adjusted' SST Data at Station 694
 (a) Original plot with 'time lagged' SST
 (b) Adjusted plot correcting time lag by moving observed SST ahead 48 hours

The time lag observed is logical to some extent when considering the time it takes GHRSSST to develop SST datasets from compiled measurements, and the number of

hours after receiving the daily SST data that Weatherflow actually uses them as model inputs (runs begin at 12z each day). Additional forecasting error may be introduced by virtue of how WeatherFlow utilizes the SST data. By ingesting the most recent SST value only once, at the beginning of the model run, atmospheric forecasts are influenced at each time step by an SST value that is more than 80 hours old by the end of the 36-hour forecast. Although WeatherFlow currently utilizes the most up-to-date SST datasets available, there is value in calculating the reduction in error associated with correcting the time lag observed in the initial MAE analysis. This involves not only correcting the 1-km SST data to reflect valid time-stamps, but also updating the SST inputs throughout model runs.

WRAMS Re-run Analysis

To test whether the procedure described above does, in fact, significantly reduce error in the 1-km SST data, additional model re-run analyses were performed. Two, 4-day periods were isolated for reassessment, July 20-23 and December 17-20, 2011. Both periods displayed consistent time-lagged 1-km data and were characterized by benign weather conditions together with significant thermal SST contrast. These conditions are meant to remove the influence of weather events that may affect the accuracy of not only the remotely-sensed SST data, but also WRAMS weather predictions. The additional analysis considered three concurrent, 36-hour, model re-runs performed for each day within the periods under re-review. Two of these ran in forecast mode with a single SST input at the beginning of the run from the original, time-lagged 1-km and 9-km data. An additional run in hindcast mode updated the corrected 1-km SST values throughout the model run in an attempt to eliminate both the initial 48-hour, and additional 36-hour, time

lags. To accomplish this, updated SST values were linearly interpolated for each time-step in the model run from the corrected, daily 1-km data.

In addition to MAE analysis, the meteorological verification statistics associated with each model run were also examined. After WRAMS completes a model, statistical analyses are performed on the output data to determine how closely the model was able to capture real atmospheric conditions. This includes examining error associated with U and V wind vector components, temperature, dew point, and wind speed. For the purposes of this application, which is improving the ability of WRAMS to accurately forecast wind, accuracy verification focused only on wind speed error.

‘Corrected’ SST Value Comparison

A comparison of the SST data used in the model re-runs with observational SST values, by station, is shown in Figures 30 and 31 for the July and December periods, respectively. Blue lines (ac1u) represent the corrected 1-km SST data, continuously updated throughout the model runs; red lines (ac1f) represent the time-lagged 1-km SST data; green lines (ac) represent the 9-km SST data currently utilized by WeatherFlow; and purple lines (obs) display the observed SST values measured during each period. The final twelve hours of each 36-hour run should have overlapping SST values with the initial twelve hours of the subsequent run, but due to a glitch in the ‘coding’ of the model associated with interpolating the ‘corrected’ 1-km SST data, all SST values for the final twelve hours of each model run were eliminated from analysis. For all stations, and throughout both periods, ac1f and ac values remain constant for the length of the 24-hour period following the start of a model run, because they were not updated throughout the run as with the ac1u SST data. In addition, due to the fact that all the datasets, including

the 'corrected' 1-km data, provide one SST value daily, they are not able to resolve the diurnal variability that exists in the observed SST.

By taking into account the differences in scale among the SST values for each station in Figure 30, a visual comparison of the SST values used in the July 20-23 re-run period suggest that the corrected 1-km data, labeled ac1u, are generally better able to capture the overall trend of the measured data, especially in Stations 689 and 694. Station 10212 stands out as the only station to fail completely (with ac1u, ac1f, and ac) in terms of representing the observed values throughout the entire 4-day period. For the period of December 17-20, represented in Figure 31, ac1u SST values from Stations 692, 694, and 10212, give a much more improved representation of observed SST values over the four day period. The modeled SST data for the other four stations appear to deviate extensively from the observed values, especially at Stations 392 and 92920.

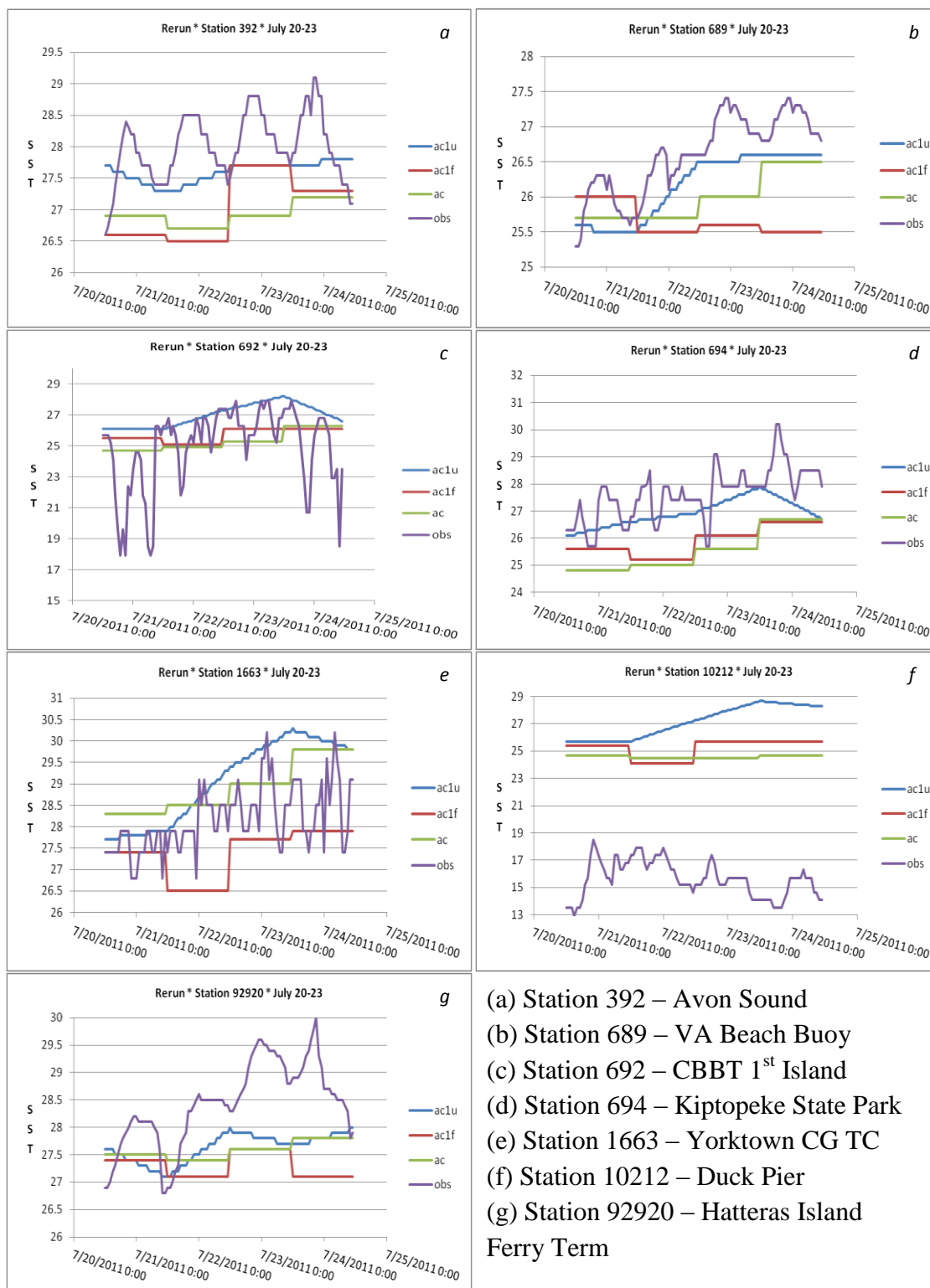


Figure 30: Corrected SST Value Comparison for Each Station, July 20-23

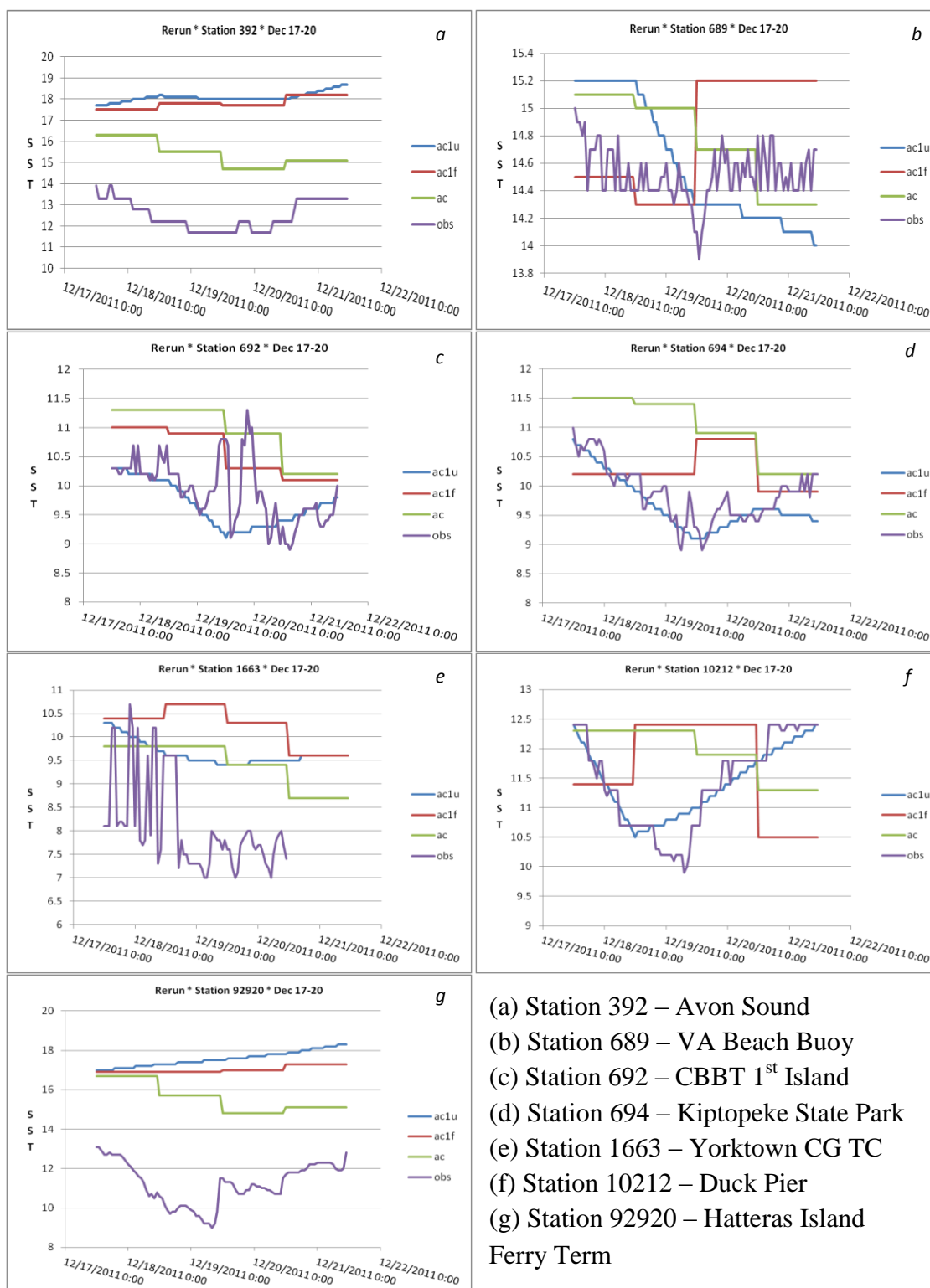


Figure 31: Corrected SST Value Comparison for Each Station, Dec. 17-20

Secondary Mean Absolute Error Analysis

MAE analysis was performed to find the average, over the sampled periods, of the absolute values of the differences between forecasted SST data and the corresponding observations. A comparison of the magnitude of the errors exhibited among each of the three types of SST data provides an indication of the value of utilizing SST data as close to real-time as possible. Table 2 below displays calculated MAE values, which show a high level of variability, ranging in value from less than a quarter of a degree at Station 694 in July to more than 11 degrees at Station 10212 in July.

Table 2: Averaged MAE Values of each SST Dataset, by Station, for July and December

	392	392	689	689	692	692	694	694	1663	1663	10212	10212	92920	92920
MAE	July	December	July	December	July	December	July	December	July	December	July	December	July	December
ac1u	0.544792	5.565625	0.451042	0.396875	2.067708	0.371875	0.821875	0.242708	0.934375	1.747917	11.52083	0.244792	0.883333	6.330208
ac1f	0.985417	5.282292	1.045833	0.432292	1.833333	0.746875	1.759375	0.592708	0.897917	2.322917	9.6	1.302083	1.195833	5.785417
ac	1.0875	2.882292	0.647917	0.388542	1.90625	1.021875	2.092708	1.138542	0.83125	1.560417	8.975	1.022917	0.960417	4.335417

These results can be more easily visualized with the graphs in Figure 32 below. Graphs (a) and (b) show the calculated MAE values for all three SST datasets at each station, averaged over the length of each period analyzed. In many situations, except for those that experience the higher MAE averages, the corrected and updated ac1u SST values experience lower error than both the 9-km and time-lagged 1-km data. This suggests that correcting time lag issues does, in fact, improve the ability of 1-km data products to capture observed SST characteristics.

Graph (c) displays the complete set of MAE values for all three SST datasets used at each station, allowing both periods analyzed to be viewed together. Three stations stand out as showing a high magnitude of error among all SST datasets tested; Station 10212 in the July period, and Stations 392 and 92920 in the December period. To more

effectively compare the accuracy of the other data, Graph (d) displays a zoomed view of Graph (c), cutting off the upper ends of those three extremely inaccurate periods. These two graphs show that a high level of variability in MAE often exists at the same station during different time periods.

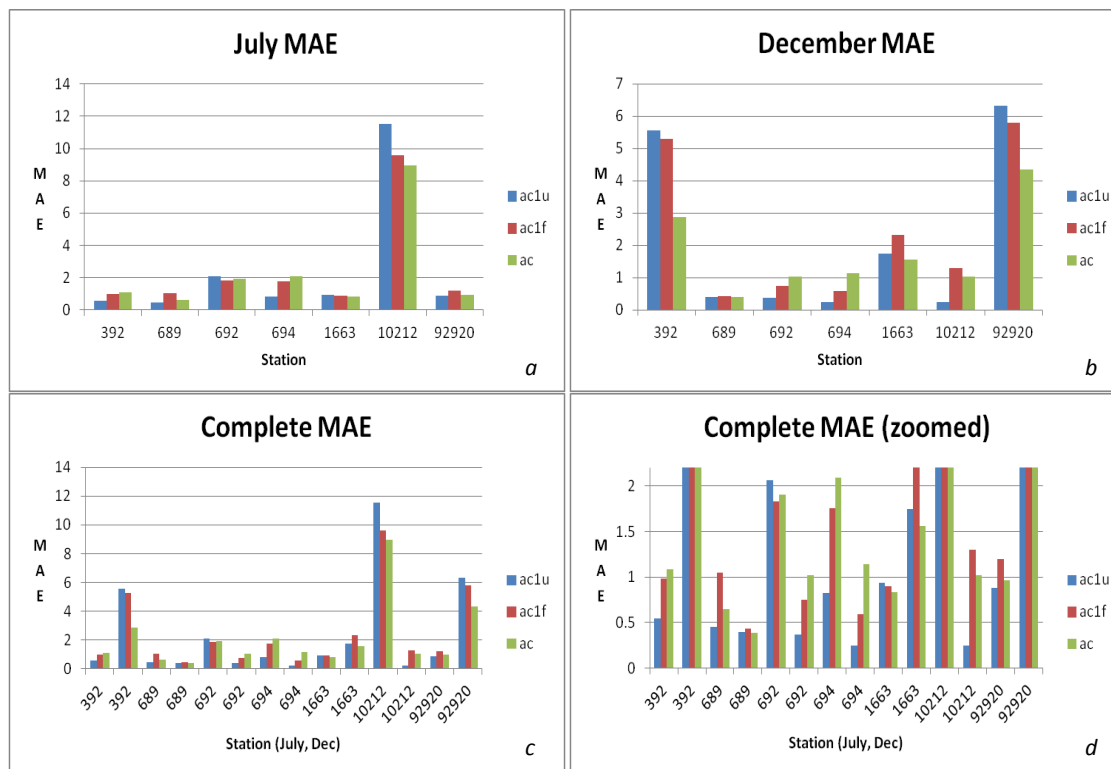


Figure 32: Averaged MAE Values of each SST Dataset

- (a) Bar chart of MAE values, by station, for July period
 (b) Bar chart of MAE values, by station, for December period
 (c) Bar chart of MAE values for all stations, broken down by period (July, December)
 (d) 'zoomed' view of (c)

The site-specific nature of some of the stations may help explain some of the variability. Figure 33 below shows a gradient map of water temperature on the first day of re-run analysis for each period. Looking at the temperatures gradient near Station 10212, which experienced the highest MAE for all datasets in July, but some of the

lowest MAE values in December, it can be seen from the multiple contour lines near the station in July that a large temperature gradient exists over a small area. This incidentally corresponded with high error observed among all SST data at that station, especially in the ac1u values. In December, however, the area near Station 10212 is covered by a single temperature contour, which corresponded with low MAE values for all SST data. The ac1u data performed especially well, experiencing an average MAE of less than 0.25 degrees over the 4-day period, which was considered the most accurate representation of SST observed in all the re-run analysis. The large number of contours present in December near Stations 392 and 92920, as opposed to July, may help explain the larger error observed in December for those stations. If the reliability of the data can be determined in this fashion, this analysis can help reduce uncertainty in the accuracy of all the forecasted SST datasets at particular locations.

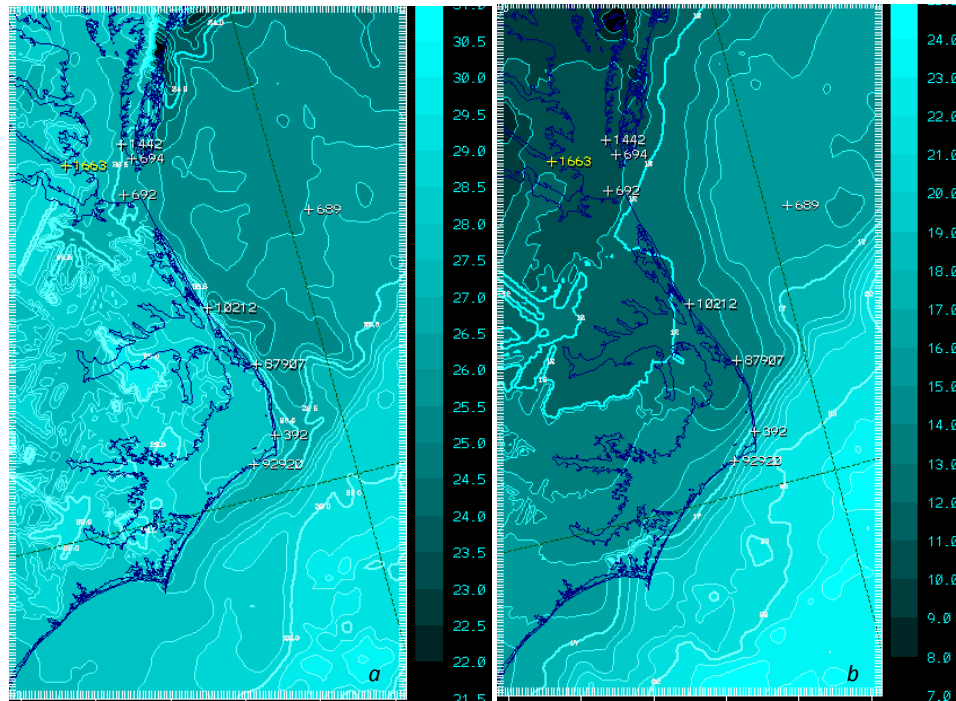


Figure 33: Contour Maps showing SST Variability over Chesapeake Bay and Surrounding Coastline
 (a) July 20, 2011 at 12:00 UTC
 (b) December 17, 2011 at 12:00 UTC

Comparison of Model Meteorological Verification Statistics

For the final analysis, the meteorological verification statistics calculated at the end of each model re-run were compared to give an indication of how the different SST datasets affected forecast accuracy. Analysis focused on projected wind speeds because of its relevance to the ‘Offshore Wind Test-Site Development Effort’ project. Model projected wind speeds for each of the four, 36-hour model re-runs during the July and December periods were plotted against the observed wind speeds during those 36-hour periods. The left columns of Figures 34 and 35 graphically display those results. In addition to comparing projected and observed wind speeds directly, MAE values were also calculated, shown in the right column in Figures 34 and 35.

From these output statistics, no discernable visible improvement in wind speed forecasting could be identified from any of the model runs. This was confirmed the MAE analysis, which failed to show reduced error in wind speed projections using the corrected SST values. Based on the improved accuracy of the corrected 1-km SST data against the observed SST values for the individual stations, it was unexpected that model performance would not reflect improvement. Had the ac1u values shown improvement in wind speed prediction, it would have justified coupling an SST forecasting mode to RAMS that would update SST inputs during model runs.

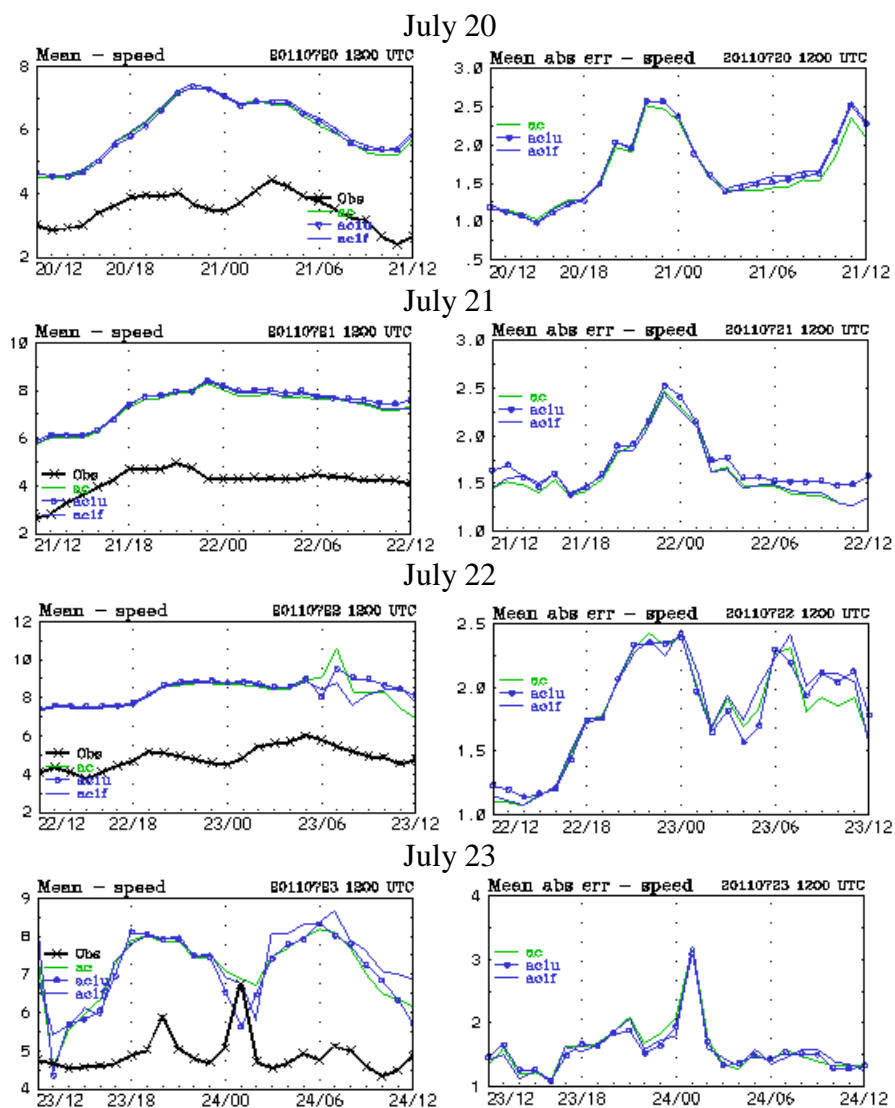


Figure 34: Observed Wind Speeds v. RAMS Model Projections and associated MAE,

July 20-23

- (obs) – Observed wind speed
- (ac) – 9-km model projections
- (ac1u) – ‘Corrected’ 1-km model projections
- (ac1f) – Original 1-km model projections

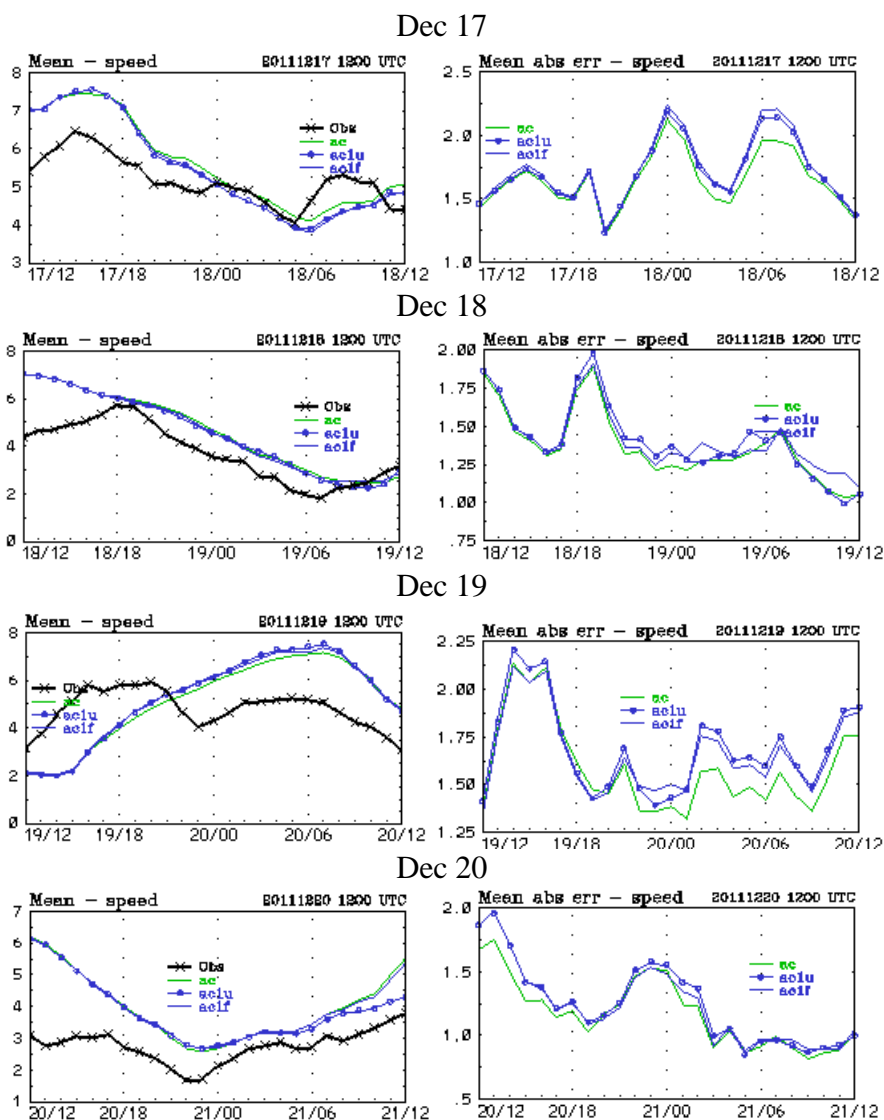


Figure 35: Observed Wind Speeds v. RAMS Model Projections and associated MAE, December 17-20

- (obs) – Observed wind speed
- (ac) – 9-km model projections
- (ac1u) – ‘Corrected’ 1-km model projections
- (ac1f) – Original 1-km model projections

Final Analysis and Conclusions

Initially the performance of the 1-km and 9-km SST data over the 45-day, ‘early winter’ sub-season was compared to observational values gathered in situ from the seven stations’ recorded SST measurements. Mean absolute error (MAE) was used to assess the

accuracy of each dataset against the observed SST measurements. From the results of this initial analysis, it was determined that the 9-km data experienced less error than the 1-km data. In an effort to understand and attempt to address these results, latency issues were corrected by adjusting the 1-km data ahead by 48-hours. MAE analysis was again performed to determine if correcting the offset improved the accuracy, which proved to be true in most cases. Finally, additional model re-runs were performed that incorporated the 'corrected' 1-km data, updated at each time-step throughout each run.

Taken together, the results of these analyses lead to a rejection of the initial hypothesis. Using the higher resolution, 1-km data stream as it arrives results in greater error than for analyses that utilize the lower-resolution data. Correction of the time lag in the 1-km data does improve its accuracy, but this does not lead to improved model performance in the case of forecasted wind speeds. Until the influences from air-sea interactions are better reflected in the dynamic equations that govern RAMS, the use of SST inputs that are simply more accurate fails to provide significant benefits for model performance, and therefore does not reduce the uncertainty associated with the reliability of wind resource assessment.

Phase Two

Chapter Five – Web Portal Development

Introduction

Offshore and coastal wind projects and research efforts result in various levels of proprietary and publicly available data that must be organized, stored, and communicated in a way that encourages national, regional, and local collaboration. An important ambition associated with data and information sharing is to keep that data as close as possible to the official, or authoritative, source that originates and maintains the attributes of entities. This ensures that the data remain accurate and current as it is managed and updated from the source. When the same data are stored in multiple locations, the potential for error increases as it becomes more possible for one or more organizations to house inaccurate or outdated data, which can lead potentially to mis-informed and costly decisions. In order to reduce these effects, data can, and should, be shared in a way that reduces duplication of efforts and streamlines the transfer process. By eliminating potential data inconsistencies through the ‘smart’ design of systems for data sharing, the access to reliable data is increased and thus some degree of uncertainty that currently hinders offshore wind development in the U.S. is reduced.

This phase of work focuses on the development of a web portal for the “Virginia Offshore Wind Advanced Technology Demonstration Site Development” project. An introduction to GIS and the structure of database systems is first provided, as well as an explanation of methods for data sharing and the importance of interoperability standards.

Evolution of Geographic Information Systems

Cartography, statistical analysis, and database technology have been merged together in the development of geographic information systems (GIS), which allow the storage, manipulation, and display of multiple forms of geospatial data (Coppock & Rhind, 1991). Geospatial data are the data or information that, for example, identify the geographic location of natural and constructed topographical features and boundaries. Before the advent of computers, manual cartographic methods severely limited the amount of information that could be contained and manipulated within a map (Coppock & Rhind, 1991). One of the first applications to isolate certain attributes of a mapped area was through photozincography. This process separated individual components of maps into transparent layers which could then be overlaid together to form an image of the complete map (Oliver, 2011). Although very time-intensive, this was one of the first processes that allowed for the identification and analysis of geographically dependent information using the semblance of a technique that would later evolve into a fundamental feature of modern GIS.

Recognized as the first truly operational GIS, the desktop system created in 1960 by the 'father of GIS,' Dr. Roger Tomlinson, for the Canada Land Inventory, mapped information about soils, agriculture, and land use, among others, in rural areas throughout Canada, and was the first to allow overlays of digitized data (Coppock & Rhind, 1991). This evolved into modern GIS applications that use geo-referencing capabilities to organize and relate information based on their spatial and temporal location. This information must first be digitized, or transformed from real objects into either vector (discrete objects) or raster (continuous fields) data, through a computer-aided design

(CAD) program, at which point it is stored, and can be visualized, using GIS software in the form of points, lines, and polygons (James, 2001). In this way, a GIS represents a database that organizes data by grouping together otherwise unrelated information as attributes of a particular location, which can then be manipulated for an infinite number of spatial analyses and modeling applications.

Due to its multidisciplinary nature, early phases of GIS development evolved independently across a variety of systems that were often ignorant of the facilities of another (James, 2001). The involvement of national agencies such as the U.S. Bureau of the Census and the U.S. Geological Survey eventually initiated standardization of geospatial data structure and metadata (Coppock & Rhind, 1991). GIS software became commercially available in the 1980s, through companies such as the Environmental Systems Research Institute (ESRI), which remains a leading commercial vendor today. By the late 1990s, GIS applications had shifted from limited desktop systems to limited-area networks (LAN), then to enterprise networks, to finally to internet applications, made possible through the development of distributed systems (Coppock & Rhind, 1991)

Distributed Systems

Within a distributed system, multiple computers can be connected through, and exchange information over, a computer network. Having evolved from smaller, localized connections to more large-scale networks such as the internet, distributed systems now allow computers all over the world to connect with one another through distributed software such as e-mail (Godfrey, 2002). Through a distributed system, an application uses a collection of protocols to communicate processes for data sharing between the

multiple entities on a network; all components cooperate together to perform a task and appear as a single system to the user (Godfrey, 2002).

The architecture of distributed systems can vary depending on the goals of the system, but are generally structured in an n-tiered, service-oriented approach, which separates system components based on their individual roles (Emmerich, 1997). This has evolved from a more general client-server model consisting of clients that request a service, or task, from a server through a network. In the most basic case, the client contacts the server for data directly, and then the server formats it internally and shifts it back to the user for display (Andrews, 2000). This means that all the software for the client for accomplishing a task must be installed on the client's own hardware, and any updates or changes must be distributed to and done individually by the user, which limits the interoperability of the system. Eventually, the client-server approach evolved into a multi-tiered structure which further separated system components by processes (Andrews, 2000).

The three main tiers are presentation, application, and storage, which are developed and maintained as individual processes. The top-most level of the application is called the presentation tier, which communicates with the other components and translates the results of a query, or other process, into something the user can understand in the form of a user-friendly interface, which can be on a personal computer using a desktop tool or through a web browser (Emmerich, 1997). The lowest level tier is the storage tier, consisting of database servers, or other storage methods, which house information of interest (Emmerich, 1997). The processing that took place at the client level in earlier client-server models has been separated into its own tier, referred to as the

logic or application tier, which coordinates the movement and processing of data between the two outer tiers. This web service layer processes all commands, performs calculations, and has logical decision-making capability. In the case of n-tiered structures, the middle tier may consist of multiple tiers itself where, instead of directly communicating with a database, the initial web service sends queries to additional web applications which have their own individual distributed structures (Godfrey, 2002).

Figure 36 below provides some examples of multi-tier architecture.

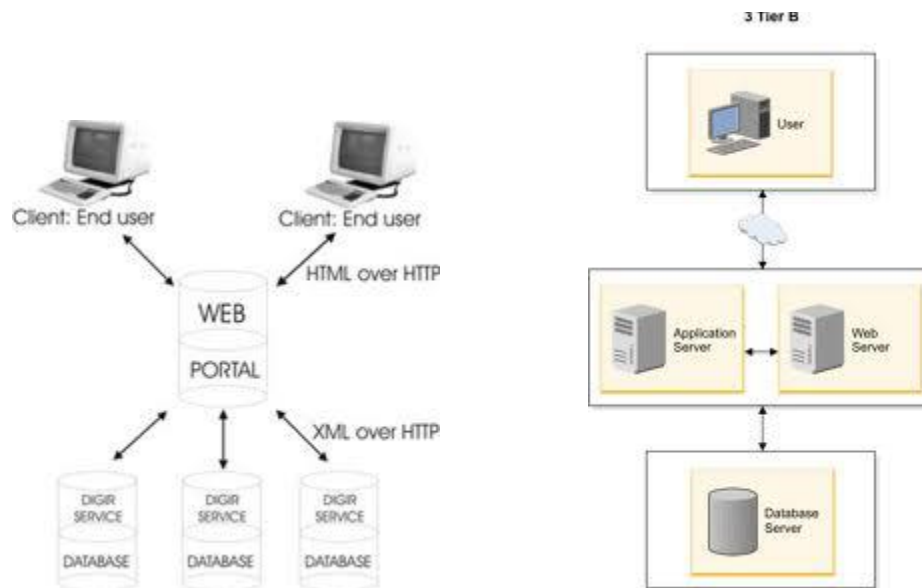


Figure 36: Examples of 3-tiered and n-tiered architecture

Sources: <http://www.marbef.org/data/eurobis.php>

http://publib.boulder.ibm.com/infocenter/pim/v6r0m0/index.jsp?topic=%2Fcom.ibm.wpc.ins.doc%2Fwpc_con_architecture.html

Web-Based Applications

One of the benefits of this expanded architecture is that it allows developers to create flexible applications, these can be modified at each individual tier rather than requiring a revision of the entire application. In this way, the multi-tiered structure of distributed applications is utilized by web developers in the creation of websites and other web applications. Comprised of multiple web pages dedicated to a particular topic,

websites are hosted on one or more web servers and are accessible over the internet through web browsers. They can be personal, commercial, or governmental; allow varying levels of user interaction; and collectively represent the contents of the World Wide Web. Following the structure of database systems, the components of a web-based application include a presentation tier, consisting of the front-end content rendered to a client through a web browser; an application tier, such as a web service, which handles all the processing and communication between system components, and a storage tier, which refers to the database or additional web service which hosts the information requested by the service tier.

Processes for Data Sharing

An application-programming interface (API) is a set of programming instructions and standards for accessing a web-based software application (Orenstein, 2000). APIs guide software-to-software communication by providing a channel for applications to work with one another to make sure the client, or end user, receives the functionality and information that has been requested. This is important in n-tiered distributed systems, where middle service tiers are further subdivided, and rather than directly querying databases, the applications must communicate with additional applications that host the data they require. APIs are specifically designed to expose only chosen functionality or data through the interface, while protecting other parts of the application. Instead of duplicating the functionality of another service, an application can access what another one offers and, through web services, combine that information with what their service provides in order to provide improved and added functionality to their users (Orenstein, 2000). Custom APIs can be created for a unique or very specialized purpose, but it is a

common practice for companies to expose part of their data or functionality as an API to others on the Web so that they can be utilized in multiples sites or applications. One of the major benefits of APIs are that they are designed so that anyone can build applications on top of those sites and services. A good example of this is the Google Maps API, which can be freely accessed to allow a website to embed Google Maps into its web pages, and includes a number of services for customizing and adding additional content.

Without standardization, the sharing of all types of geospatial information among web services and applications across the web can be limited by the interoperability of the interface. If the data or functionality of a web service is meant to be available for other systems to use, it must describe its capabilities and present a standard protocol for communication with an application. These standards offer existing codes for many types of communication, which often eliminates the need to write custom code and supports the sharing of geospatial data and spatial analysis tools between systems in an efficient manner. The Open Geospatial Consortium (OGC) is a non-profit organization that has dedicated itself to developing, through a consensus of over 400 companies, government agencies, and academic institutions, publicly available interface standards for geospatial data (OGC, 2012). It is the vision of the OGC to ‘make geospatial information and services available across any network, application, or platform,’ by creating open standards and architecture that enable the integration of complex spatial information and services into other user applications (OGC, 2005).

At present, there are more than 30 different OGC web standards that serve specific geospatial interoperability needs. Some of the more relevant standards for the

web portal designed for the “Virginia Offshore Wind Advanced Technology Demonstration Site Development” project include web map services, web coverage services, and web feature services. The OpenGIS Web Map Service Interface Standard (WMS) is a protocol for sharing geo-referenced map images over the internet between distributed geospatial databases and web applications (OGC, 2005). It can produce a map of geographic feature data and answer basic queries about the map’s content. In contrast to a WMS, the OGC Web Coverage Service Interface Standard (WCS) is intended to provide access to the original raster data with its inherent values, allowing the user to then edit the data or perform additional spatial analysis (OGC, 2005). OGC Web Feature Service Interface Standards (WFS) are intended to provide similar capabilities as WCSs, but by sharing of geographic feature data in the form of points, lines, and polygons (OGC, 2005).

“Virginia Offshore Wind Advanced Technology Demonstration Site Development” Project Web Portal

Web Portal Deliverable

One of the deliverables associated with the “Virginia Offshore Wind Advanced Technology Demonstration Site Development” project is to develop a website dedicated to the broader effort that will not only dynamically display project results and outcomes, but eventually serve as a portal for facilitating communications and collaborative efforts to promote the development of the offshore wind industry in the Commonwealth. The goals of this work are to create a site that centralizes offshore wind energy information, provide convenient access to useful topics, resources, and data for learning about or

investing in offshore wind, and serve as an initial guide for organizations interested in implementing offshore wind energy infrastructure.

The general website consists of multiple sub-pages, each dedicated to its unique objectives. Some will provide users information about current projects, such as the “Virginia Offshore Wind Test Site Development Effort” project as well as projects completed in the past and even student work. Another will focus on offshore wind energy education, with informative sections on wind farm design, interconnection and electricity production, environmental and economic issues related to development, and other general information. It will also provide links to related publications, press releases, and information about upcoming and past meetings and events.

Web Mapping Component

Another major element of the website effort was the design of a web mapping component, which was developed through a collaborative effort between JMU and project subcontractors, Timmons Group and WeatherFlow, and explores Virginia’s wind energy potential by integrating open metocean data sources from other web services and displaying current project results. This mapping component is split into two web-viewer portals, the first of which explores Virginia’s offshore wind energy potential, while the second integrates project deliverables and relevant open source data into a Virginia coastal waters focused map.

Specifically, the ‘Wind Resource and Energy Viewer for Virginia Offshore Wind Space,’ shown in Figure 37 below, exploring Virginia’s offshore wind energy potential includes a base map of Virginia’s coastal waters that displays real-time wind conditions and estimates of how that translates to energy production. Selecting any weather station

shown on the map allows users to view a pop-out box that provides real-time, observational metocean data. This provides an indication of the surface-level wind and water conditions throughout state and federal waters off the Virginia coastline. In addition, the user can click on any other point in the map, including any lease block within the Virginia WEA, and an energy summary pop-out window appears that provides extrapolated current conditions. Further, it displays energy forecast data modeled assuming a generic wind turbine with hub height of 100 m, and includes average wind speeds and simulated energy productions (MWh) for the NREL 5-MW turbine (NREL, .

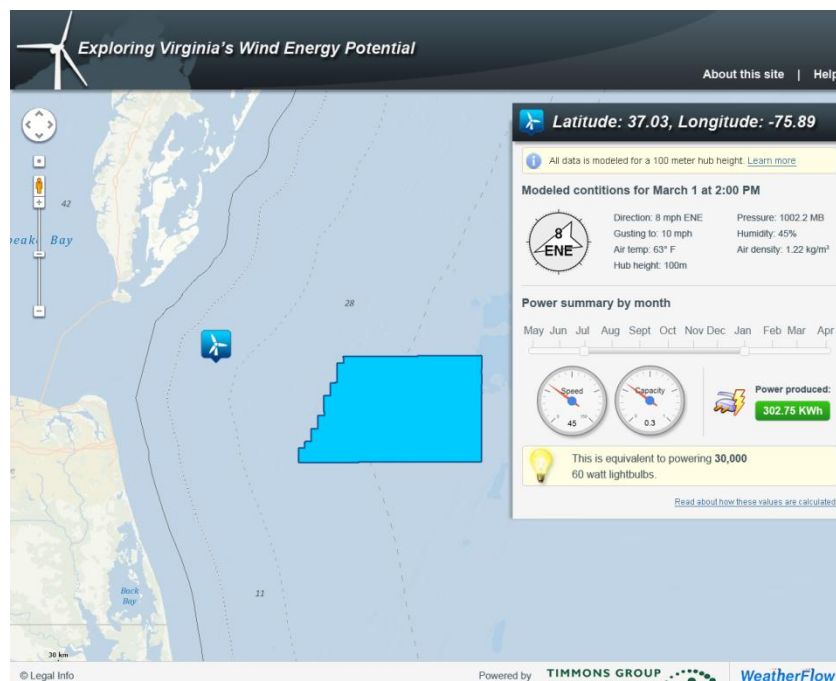


Figure 37: Screen-Shot of Layout for the ‘Wind Resource and Energy Viewer for Virginia Offshore Wind Space’

The second portal, ‘Map and Data Viewer for Virginia Offshore Wind Space,’ includes the same Virginia coastal waters base map utilized in the first portal, but instead of displaying wind data, it provides other information and data related to site development. A screen-shot depicting the potential layout for the portal is shown below in Figure 38. The portal incorporates publicly available datasets made available through

the Multipurpose Marine Cadastre (MMC), a marine information system that provides authoritative and regularly maintained ocean data in a common GIS framework. Of the 136 jurisdictional, legal, physical, ecological, and human use data layers provided, 12 are utilized; these include the OCS lease blocks, BOEM wind planning areas, Navy operation areas, shipping wrecks and obstructions, military danger zones, Navy aviation warning areas, aids to navigation, habitat areas of particular concern, sediment type, seafloor geology, bathymetric contours, and offshore wind resource potential. It will provide links to MMC and other websites with additional open source marine geospatial data, including Coastal Gems, Marco, and OceanGIS.

The portal also provides users with the ability to view geographic project data at specific points on the map, including the Chesapeake Bay Bridge Tunnel and Monitor Merrimac Bridge Tunnel site maps, concept plans, and visual simulations. It also allows other non-geographic specific project data to be accessed as portable document format (PDF) links to static reports including the Fugro Geosciences Focused Desktop Study, historic wind and weather data and analysis provided by Old Dominion University, and WeatherFlow's sub-season meteorological report.

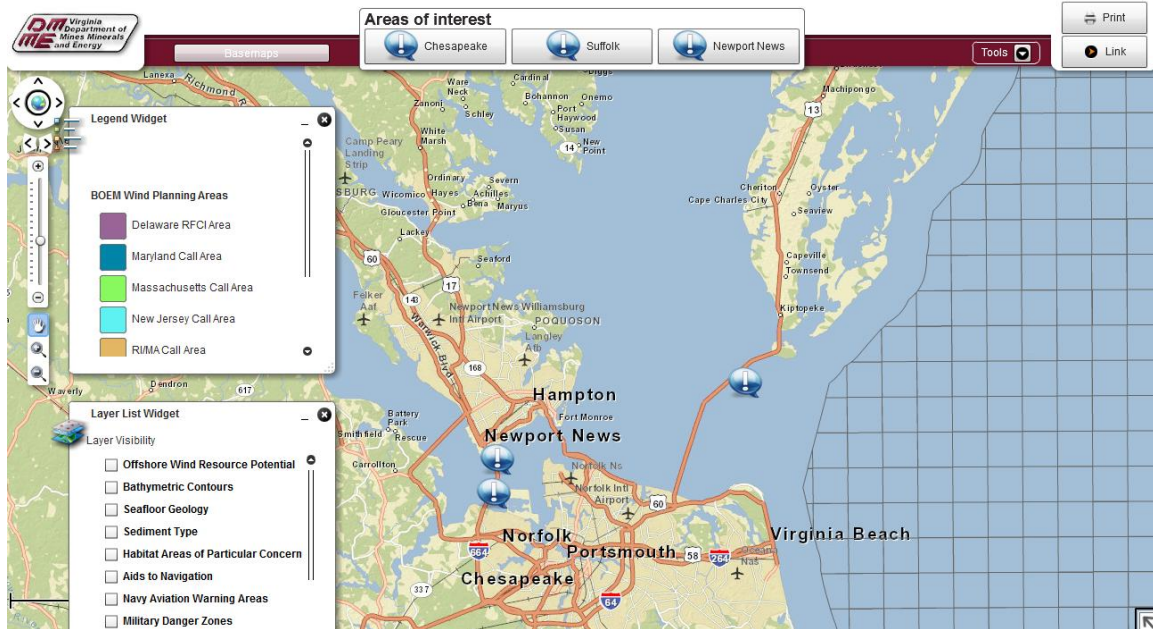


Figure 38: Screen Shot of Layout for the ‘Map and Data Viewer for Virginia Offshore Wind Space’

Map Component Structure

A major focus of the design and development of the mapping component has been to ensure an architecture that supports ‘smart’ data sharing practices. Rather than duplicating the functionality and downloading the data hosted through other sites, the portals have been designed to utilize APIs and standards for web mapping services that access the data while allowing it to remain hosted as closely as possible to the authoritative source.

For the historical and real-time wind data visualized in the ‘Map and Data Viewer for Virginia Offshore Wind Space,’ WeatherFlow remains the authoritative source of the data collected from its own sensors, but allows some information to be shared through a custom API they developed that controls what information the web portal can access and utilize for its mapping application. In this way, WeatherFlow can protect a majority of its proprietary data from view. Specifically, the API specifies instructions for how data

requests be made, and indicates what information will be provided by WeatherFlow. At specific stations, the metadata, such as coordinates and sensor height, are included with the latest observations of wind speed, direction, and gust, as well as air and water temperature, and air pressure. Further, current interpolated hub-height conditions are available for any point on the map; the data included are WRAMS projected wind speed, direction, and shear, as well as additional measures of humidity and air temperature, density, and pressure. Finally, the API delivers energy climatology for periods of interest at requested locations within the map-viewer, providing average wind speeds, energy production, and capacity factors. Timmons Group and JMU have developed a GIS map portal interface to display the data from WeatherFlow's API.

For the second portal, 'Wind Resource and Energy Viewer for Virginia Offshore Wind Space,' Timmons Group and JMU have developed a GIS map portal that uses ArcGIS Server, a web mapping API that allows users to build and develop applications that include GIS functionality and web services. The portal utilizes an Adobe Flash media platform for interactivity through a software development kit, Apache Flex. The 12 open source data layers are accessed as map services from MMC and loaded into the web-viewer. The user will have the ability to turn layers on and off, as desired, as well as view the geographic-specific project results as PDFs and images as they scroll over the indicated sites. In addition, the specific functionality of the website includes a splash page introducing the user to the web map and how it can be used, graphical map features such as scale and compass displays, the ability to zoom and pan, and tools for sketching points, lines, and polygons.

The main website, with both web mapping components included, are hosted on multiple physical servers at JMU. The website is maintained by JMU's Creative Services department, while clicking on either of the mapping component links will transfer the user to a separate web page hosted by a server specifically used by the VCWE. The 'coding' for both mapping component interfaces was provided by Timmons Group, and once uploaded to the server, the interfaces were automatically transferred and became operational.

Conclusions

The development of distributed systems has facilitated the sharing of geospatial data across multiple platforms around the world. Although the deliverables associated with the "Virginia Offshore Wind Advanced Technology Demonstration Site Development" project were limited in terms of the scope of what was specifically required, the web mapping components of the website were designed in a way that encourages the dissemination and sharing of publicly accessible offshore wind and other related data. Standard web service protocols allow the 'Wind Resource and Energy Viewer for Virginia Offshore Wind Space' portal to utilize and display data that is not actually hosted on a JMU server. This demonstrates 'best practices' for interoperability since the data are hosted by the authoritative source and are therefore less prone to accumulating errors. The two web mapping components not only displays project data and results, but provide an indication of micro-scale wind resource characterization and corresponding energy potential, thereby reducing some of the data uncertainty issues related to offshore wind development in Virginia.

Chapter Six: Conclusions and Recommendations

Conclusions

Although there are no offshore wind installations constructed in the U.S. to date, a demonstrated wind resource exists, and recent efforts have sought to significantly advance the development process and promote robust industry growth. This has involved collaborative efforts among federal, state, and local government agencies, as well as multiple academic, private, and non-profit organizations, all of which has been facilitated by the sharing of reliable data pertaining to offshore wind development. The “Virginia Offshore Wind Advanced Technology Demonstration Site Development” project is one of many federally supported efforts aimed at addressing the uncertainty and issues that present barriers to U.S. offshore wind development, including the scarcity of reliable, site-specific wind data and resource characterizations.

Phase One of this effort addresses this need for improvements to metocean data and modeling for wind resource characterization through an evaluation of a proposed SST improvement to WeatherFlow’s RAMS, which is utilized to provide wind resource information under the auspices of the “Virginia Offshore Wind Advanced Technology Demonstration Site Development” project. Initially, the increase in error demonstrated by MAE analysis comparing the higher resolution (1-km) SST data to observational values suggested that WeatherFlow would do just as well continuing to utilize their current 9-km SST data. In an effort to address these counterintuitive results, latency issues identified in the 1-km data were recognized and updated model runs performed. Although the MAE analysis of the ‘corrected’ 1-km data demonstrated a reduced level of error, this did not translate to an improvement in model performance for forecasted wind speeds. The

results of these analyses led to the rejection of the initial hypothesis that higher resolution input data would improve WRAMS forecasting ability and thereby reduce reliability issues related to wind resource characterization which influence offshore wind development.

Chapter 3 demonstrated that heat exchange between the sea surface and the atmosphere creates weather phenomena that influence wind conditions, which indicates that accurate SST data should affect the forecasting ability of atmospheric models. For this reason, it can be inferred that these model results were observed because the dynamic interactions are not yet fully captured by the atmospheric modeling equations that govern RAMS, and until they are better understood the 1-km SST datasets will not provide a useful upgrade. Therefore, although higher resolution data are generally preferred, the proposed model improvements in this particular application do not improve forecasting ability or reduce uncertainty associated with modeled wind resource assessment.

In addition to the uncertainty regarding the reliability of the very limited quantity of critical wind resource data that does exist, said data are often represented in various formats and fragmented across multiple individual applications. Phase Two addresses this issue of data accessibility within the “Virginia Offshore Wind Advanced Technology Demonstration Site Development” project. The two web mapping components developed for the general project website were designed in a way that encouraged the dissemination and sharing of publicly accessible offshore wind and other related data. They display not only project results and other data related to offshore wind, but characterize the micro-scale wind resource by applying observational and historic data and providing corresponding hypothetical energy potential. By stressing the importance of using

standard protocols for data sharing, the web portal designs encourage interoperability and collaboration, which is a necessary contribution toward overcoming the barriers to developing offshore wind in the U.S.

Although the specific data challenges pertaining to the “Virginia Offshore Wind Development Effort” project demonstrate the importance of reliable and accessible data toward reducing uncertainty and removing some of the market barriers to offshore wind deployment, the issues identified in no way encompass all of the challenges which hinder development. The U.S. continues to make significant progress toward the deployment of offshore wind, but it will still be a number of years before an offshore installation is constructed.

Recommendations

There are a number of opportunities for further study within both phases of this work. In reference to Phase One, it would have been informative to test whether using the observed SST values that were physically measured as inputs for hindcast model re-runs would have affected forecasting accuracy. This would provide an indication of the maximum ability of RAMS to capture sea surface interactions with the atmosphere, and provided more insight as to next steps for further addressing this forecasting problem. Additionally, had time constraints not limited the extent of the web portal development, it would have been informative to investigate the outcomes of incorporating additional wind data from other sources into the micro-scale wind resource calculations. This would provide additional verification for the modeled hub-height conditions and hypothetical energy output potential calculations.

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