PaHM

Generated by Doxygen 1.9.5

Chapter 1

PaHM Manual

Parametric Hurricane Modeling System

User's Guide

Panagiotis Velissariou panagiotis.velissariou@noaa.gov

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Chapter 2

Abstract

Over the years, various parametric wind models have been developed to estimate the surface winds within a tropical cyclone given the track of the storm. Such models can be very useful on forcing ocean and wave models in storm surge simulations, as they are lightweight and they do not require much time or computational resources to produce the wind fields on the fly for the duration of the storm. The Parametric Modeling System *PaHM* (https://github.com/noaa-ocs-modeling/PaHM) is developed to be used as a general atmospheric modeling system to support coastal applications.

PaHM is an ESMF/NUOPC compatible modeling system that can be used either as a standalone atmospheric model, or as an atmospheric modeling component coupled with ocean and wave models via NOAA's Environmental Modeling System (`NEMS`), a common modeling coupling framework that implements the National Unified Operational Prediction Capability (`NUOPC`). The core modeling components of the system are the Holland Models ([1980], [2010]) and the Generalized Holland Parametric Tropical Cyclone Model (Gao et al. [2015], [2018]).

PaHM is developed at the Coastal Marine Modeling Branch under the office of Coastal of Coast Survey at NOAA's National Ocean Service. In a "standalone" configuration it ouputs gridded atmospheric fields to force any ocean/wave model while, in its "coupling" configuration, it feeds the atmospheric fields to the couple ocean/wave model via its own NUOPC Cap. The source code of *PaHM* can be accessed at: https://github.com/noaa-ocs-modeling/PaHM.

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Introduction

Over the years, various parametric wind models have been developed to estimate the surface winds within a tropical cyclone given the track of the storm. Such models can be very useful on forcing ocean and wave models in storm surge simulations, as they are lightweight and they do not require much time or computational resources to produce the wind fields on the fly for the duration of the storm. The Parametric Modeling System *PaHM* (TEST) is developed to be used as a general atmospheric modeling system to support coastal applications.

5.1 The Parametric Hurricane Modeling System (*PaHM*)

The Parametric Hurricane Modeling System is not an atmospheric model but rather an atmospheric modeling system that contains multiple parametric tropical cyclone (TC) models that can be activated during run time to generate the required atmospheric wind fields. The core parametric models in *PaHM* are the Holland models (1980, 2010) and the Generalized Asymmetric Vortex Model (GAHM). Two additional parametric modeling components are in development namely, the Rankine Vortex Model and the Willoughby Model.

PaHM reads "best track" type of files (e.g., those produced by the National Hurricane Center) to generate gridded atmospheric fields (usually, 10-m wind velocities and atmospheric pressures converted to mean sea level). The file formats currently recognized by *PaHM* are: (*a*) `a/b-deck`, (*b*) `HurDat2`, (*c*) `IBTrACS` and (*d*) `TCVitals`. *PaHM* has a built-in CSV I/O interface therefore, it can read and write any of these files in ASCII format. Furthermore, *PaHM's* built-in GRIB1/2 and NetCDF interface can also be used to read other external atmospheric data products.

5.2 Downloading *PaHM*

The latest source code of *PaHM* can be downloaded from its Git repository at: https://github.com/noaa-ocs-modeling/PaHM. Binary distributions of *PaHM* are not currently available. The online documentation of the modeling system is hosted by GitHub Pages: `https://noaa-ocs-modeling.github.io/PaHM/html/index.html`. The PDF version of the online documentation can be downloaded from: `https://noaa-ocs-modeling.github.io/PaHM/pahm_manual.pdf`.

New Git users are invited to read some online guides to get familiar with vanilla Git concepts and commands:

- Basic and advanced guide with the Git Book.
- Reference guides with the Git Reference.
- GitHub reference sheets with the GitHub Reference.
- Manage your GitHub repositories with Git Using Git.

From *PaHM's* Git repository you can clone or download the the source code as follows:

- Clone the source using the command:
  `git clone https://github.com/noaa-ocs-modeling/PaHM PaHM`
- The source can be downloaded directly from:
  `https://github.com/noaa-ocs-modeling/PaHM/archive/refs/heads/main.zip`

5.2.1 Directory Structure

Now after downloading the *PaHM*, let us look at the physical directories and the configuration files that come with the system. In the *PaHM* ROOT directory contains the source and all configuration files requited to build and run *PaHM* (see Figure 1). The directories of special interest to us are `src`, `scripts`, `cmake` and `inputs`.

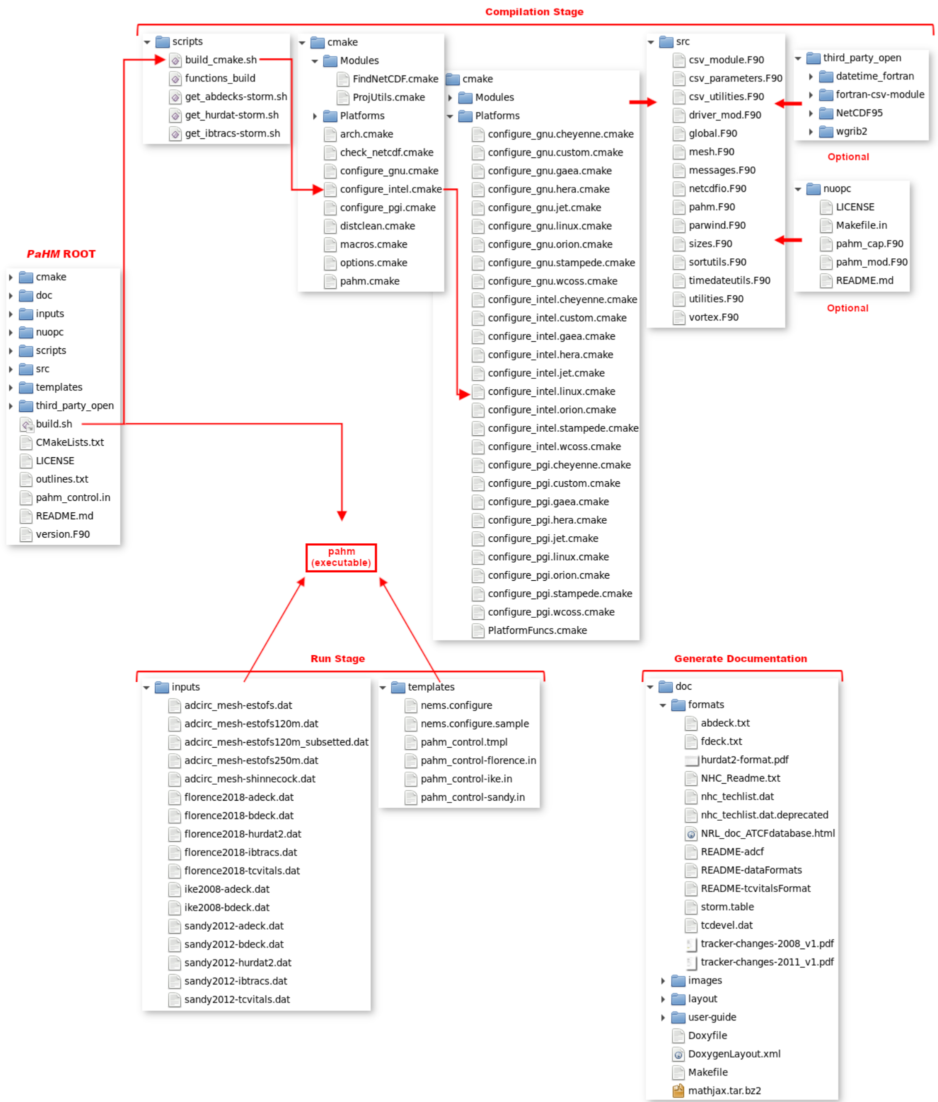


Figure 1: Directory tree of the *PaHM* modeling system.

- `src`
  Contains all the Fortran code of *PaHM*
- `build`
- `cmake`

- `third_party_open`
- `nuopc`
- `inputs`
- `templates`
- `doc`

5.3 Building *PaHM*

5.3.1 System Requirements

5.3.2 The Build System

```
Usage: "build.sh" [{-|--}option1{=|space}[option_value1] [{-|--}option2{=|space}[option_value2]] ...

  -h|-help|--h|--help
    Show this help screen.

  -c|--c|-clean|--clean [=|space] "0|1|2|-3|-2|-1|yes|no" (OPTIONAL).
    Only clean the already compiled CMake build system.
    Default: 0|no.
    Example: --clean=1   Clean the system (make clean) and exit.
                    =2   Completely clean the system (make distclean) and exit.
                    =-1  During the compilation stage, clean the system (make clean)
                         and continue with the compilation.
                    =-2  During the compilation stage, completely clean the system (make distclean)
                         and continue with the  compilation.
                    =-3  Do not clean anything but continue with the compilation.
                    =0   Do not clean anything (default).

  -cmake_flags|--cmake_flags [=|space] "cmake_flags" (OPTIONAL).
    Additional flags to pass to the cmake program.
    Example: --cmake_flags="-DFLAG1=VAL1 -DFLAG2=VAL2 ...".
    Default: none.

  -compiler|--compiler [=|space] "compiling_system" (OPTIONAL).
    The compiling system to use (gnu, intel, pgi).
    Default: none.

  -j|--j [=|space] "N" (OPTIONAL).
    Define the number of make jobs to run simultaneously.
    Default: 1.

  -par|--par|-parallel|--parallel [=|space] "0|1|yes|no" (OPTIONAL).
    Activate the use of parallel compilers.
    Default: 0|no.

  -plat|--plat|-platform|--platform [=|space] "platform" (OPTIONAL).
    The name of the compute HPC platform to consider.
    Selecting a platform additional macros are defined for the
    compilation stage that are specific to that platform.
    Supported platforms: custom, linux, cheyenne, gaea, hera, jet, orion, stampede, wcoss.
    Default: OS.

  -prefix|--prefix [=|space] "install_dir" (OPTIONAL).
    The path to the installation directory.
    Default: The location of this script.

  -proj|--proj [=|space] "project_dir" (OPTIONAL).
    The path to the user's project directory.
    Default: The location of this script.

  -t|--t|-type|--type [=|space] "cmake_build_type" (OPTIONAL).
    To set the CMAKE_BUILD_TYPE option (Debug Release RelWithDebInfo MinSizeRel).
       D = Debug.
       R = Release.
      RD = RelWithDebInfo.
      MR = MinSizeRel.
    Default: R.

  -v|--v|-verbose|--verbose [=|space] "0|1|yes|no" (OPTIONAL).
    Enable verbosity in the make files during compilation.
    Default: 0|no.
```

5.3.3 CMake Configuration Files and Modules

5.3.4 Installation

Installation and developement of *PaHM* is done through the distributed version control system Git. Even if a tarball could be sufficient, we advise to use Git system to follow *PaHM* development and merge easily to new versions. Building *PaHM* from sources requires to compile third party libraries and the use of CMake. These points are detailed below.

5.4 Using *PaHM*

PaHMcan accommodate the presence of multiple storms in the basin(defined by the input of multiple cbest trackd files)

Inputs:a cstorm trackd and a cgrid/mesh

Procedure:

Converts the cbest trackd 10-m wind values to gradient wind values.

Applies the parametric model (Holland) to generate the wind fields at the gradient level.

Converts the Pham generated wind fields to 10-m winds.

Writes the data to a NetCDF-4 file.

Wind speeds outside the last closed isobar are set to zero, while the atmospheric pressure is set equal to 1013.25 mb

In the presence of multiple storms PaHMconsiders the possible interaction between the storms when generating its gridded wind fields

Atmospheric fields are shared with the ocean and wave models using PaHM9s NUOPC/ESMF Output data:

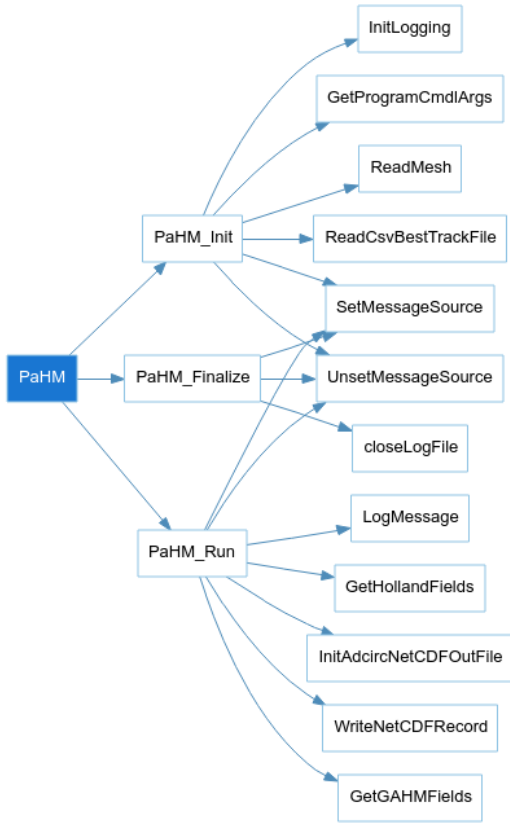
Gridded wind fields in NetCDF, CF compliant format

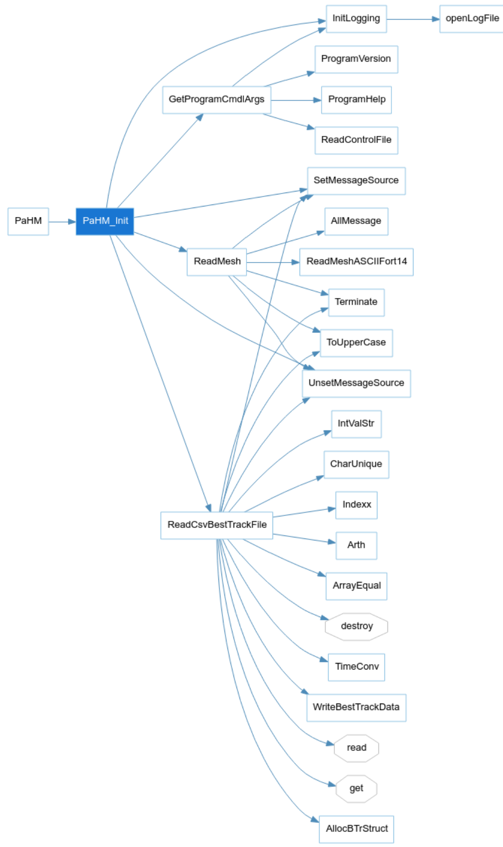
Correctedd best track data files Required inputs:

PaHM9scontrol file

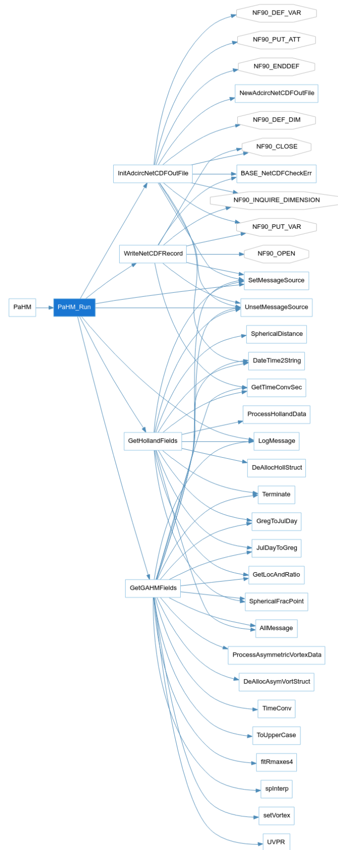
List of cbest trackd files for the basin

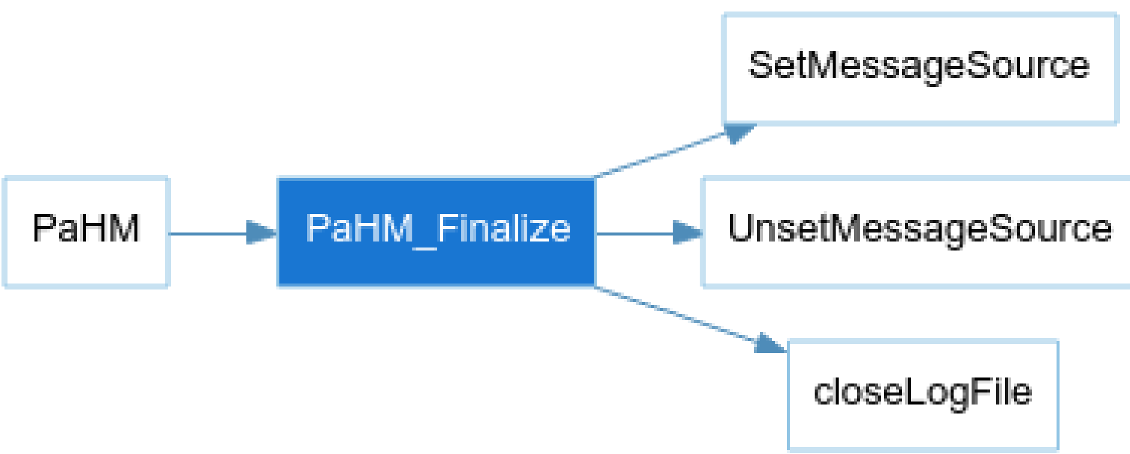
The grid/mesh file to generate wind fields for


InitLogging
GetProgramCmdlArgs
ReadMesh
PaHM_Init
ReadCsvBestTrackFile
SetMessageSource
PaHM
PaHM_Finalize
UnsetMessageSource
closeLogFile
LogMessage
PaHM_Run
GetHollandFields
InitAdcircNetCDFOutFile
WriteNetCDFRecord
GetGAHMFields



InitLogging
openLogFile
ProgramVersion
GetProgramCmdlArgs
ProgramHelp
ReadControlFile
SetMessageSource
PaHM
PaHM_Init
AllMessage
ReadMesh
ReadMeshASCIIFort14
Terminate
ToUpperCase
UnsetMessageSource
IntValStr
CharUnique
Indexx
ReadCsvBestTrackFile
Arth
ArrayEqual
destroy
TimeConv
WriteBestTrackData
read
get
AllocBTrStruct





5.4.1 Standalone Configuration

Standalone modeling system that reads “best track” type files (e.g., National Hurricane Center) to generate gridded atmospheric fields (10-m wind velocities, MSL atm. pressure) Formats recognized: a/b-decks, HurDat2, IBTrACS, TCVitals (PaHM has a csv I/O interface therefore, it can read and write any “csv” formatted “track” file) Uses symmetric and asymmetric vortex parametric TC models to generate its wind fields Currently: Symmetric models: Holland 1998 (functional), Holland 2010 (functional), Willoughby 2004 (in progress); Asymmetric models: Generalized Holland 2015 (GAHM, in progress) PaHM can accommodate the presence of multiple storms in the basin (defined by the input of multiple “best track” files) The system has a GRIB1/2 and NetCDF interface to read external atmospheric data products

5.4.2 Coupling Configuration

The coupled modeling approach described here allows to address the impacts of extreme storm events such as hurricanes on coastal areas. The HSOFS modeling system is applied and evaluated for Hurricane Florence on the Eastern coast of the US that includes the important basins of Delaware Bay, Chesapeake Bay and the Carolinas. While individual modeling components (ADCIRC, WAVEWATCH III) have already been evaluated successfully using standard statistical measures, PAHM is currently evaluated as part of the overall HSOFS evaluation. Initial HSOFS simulations show promising results on predicting total water level and flood inundation.

Initial work has been done to couple the ADCIRC hydrodynamic surge model with the WAVEWATCH III wave model (Moghimi et al. [2019, 2020]) within the NOAA Environmental Modeling System (NEMS), a common modeling framework for coupling and sharing information between NOAA’s models. This coupled wave-surge modeling system is tested by enhancing it for use in an operational setting with the HSOFS grid and modeling system. A key component of this implementation is the inclusion of parametric hurricane wind forcings. To accomplish this in NEMS, a National Unified Operational Predication Capability (NUOPC) cap has been developed to exchange the wind forcing information with both ADCIRC and WAVEWATCH III within the coupled framework.

Chapter 6

Parametric Models in *PaHM*

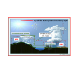
PAHM contains various light-weight parametric tropical cyclone (TC) models that require minimal computational resources to produce the wind fields on the fly and fast. Such models use limited physics in producing "accurate" wind fields in the vicinity of the storm's path. The wind fields are generated at the gradient level (Figure

PAHM generates its wind fields at the gradient level. The gradient level is roughly 1 km above the surface of the earth, and is the level most representative of the air flow in the lower atmosphere immediately above the layer affected by surface friction. This level is free of local wind and topographic effects (such as sea breezes, downslope winds etc). The 10-m wind may be estimated by decreasing the gradient level wind speed by approximately 20% over the ocean, 40% over land.

Timely and accurate estimate of the surface pressure and wind fields of a tropical cyclone (TC) is critical to storm surge forecasting and coastal risk assessment. Currently, prediction of a TC's wind field can be achieved through multiple approaches. One approach is through the use of atmospheric models, which are either statistical, dynamical, or combined statisticaldynamical, to obtain wind forecasts or nowcasts. The statistical ones empirically predict the evolution of a TC by extrapolating from historical datasets, while the dynamical models solve the full set of primitive equations of fluid flow in the atmosphere to obtain numerical results, which are quite computationally intensive. In recent years, the kinematic analysis approach showed promise to offer more realistic and accurate wind estimates, either in real-time or in hindcast mode. One example is the Surface Wind Analysis System (H∗Wind) operated by the Hurricane Research Division (HRD) before 2014, which produces H∗Wind snapshots of TCs from 1993 – 2013 by assimilating all available surface wind observations (e.g., from ships, buoys, coastal platforms, reconnaissance aircrafts, and satellites, etc.) into a common framework for height (10m), exposure, and averaging period (Powell et al., 1996). Given its versatile inputs, the H∗Wind products are considered to be among the most sophisticated and reliable surface wind reconstructions.

A third approach, which is the parametric approach, is favored for its simplicity and lower coast that are vital for timely operational forecasting. In this approach, the surface wind 2 field of a TC can be estimated as the sum of the storm vortex winds and the background winds of the environment. The vortex winds are usually depicted by a radial wind profile, whose formula is either derived from the gradient or cyclostrophic wind balance equation, or simply an empirical expression acquired from historical storm events. The background winds are of a much larger scale, and among other factors, are responsible for steering the movement of a TC (Shapiro, 1983) and considered to account for some of the asymmetry observed in the overall wind field. Currently, there is no clear consensus on how to determine the distribution of background winds due to insufficient observational data. In many applications, it was common to set the background winds equal to the storm's translational velocity (e.g., Powell et al., 2005; Mattocks and Forbes, 2008), while in many others, the background winds were assumed to be in the same direction as but with reduced magnitudes by various factors (e.g., radially varies between 0-0.5 by Jelesnianski et al., 1992, Phadke et al., 2003, and Hu et al., 2012; azimuthally varies between 0-0.5 by Georgiou, 1985, and Xie et al., 2006; constant 0.6 by Emanuel et al., 2006; constant 0.5 by Lin et al., 2012a). Lin and Chavas (2012b) introduced a methodology via vector decomposition of H∗Wind surface wind fields to investigate the relationship between the surface background winds and , and found that statistically the surface background winds are reduced by a factor of = 0.55 and rotated counter-clockwise (in the Northern Hemisphere) by an angle of = 20° relative to . The classic Holland Model (HM, 1980) is one of most commonly used analytical vortex models, which is also one of the meteorological forcing options in the ADCIRC storm surge model (NWS = 19). A thorough look at its formulation reveals that the HM suffers a few flaws due to the assumptions made during its derivation. Development of a more generalized Holland Model is presented in Chapter 2.

Given storm characteristics (i.e., track, intensity, and size), the axisymmetric component of the surface wind may be estimated by calculating the wind velocity at gradient level with a hurricane wind profile and translating the gradient wind to the surface level with an empirical surface wind reduction factor (SWRF) [Powell et al., 2003] and inflow angle [e.g., Bretschneider, 1972] to account for the effect of surface friction on the storm. (A boundary layer model [e.g., Thompson and Cardone, 1996; Vickery et al., 2009b; Kepert, 2010] may be applied to more accurately calculate the surface wind from the gradient condition, but it is nonparametric and more computationally expensive.) A number of gradient wind profiles [e.g., Holland, 1980; Jelesnianski et al., 1992; Emanuel, 2004] have been widely used in wind and surge analysis, but the wind and surge calculated using these profiles have yet to be compared in a statistical sense (though case studies do exist [e.g., Phadke et al., 2003]). Although it may be difficult at this point to identify the "best" wind profile, as each profile has its own strengths and limitations, the knowledge of how wind and surge estimates vary with different profiles is necessary in uncertainty analysis. It is also useful to investigate the sensitivities of wind and surge estimates to the effect of surface friction on the storm, for example, by examining the sensitivities to SWRF and inflow angle, the values of which have not been agreed upon [Vickery et al., 2009a] and may vary with storm conditions and wind speeds [Powell et al., 2005]



6.1 Holland 1980

The traditional Holland Model (Holland 1980), thereafter HM80, is one of most widely used tropical cyclone (TC) analytical vortex models to generate meteorological forcings near the path of the storm. HM80 solves the reduced physics gradient wind equation 6.1. Gradient winds are those theoretical winds that blow parallel to curved isobar lines or height-contour lines in the absence of turbulent drag (gradient level winds). The gradient level is roughly 1 km above the surface of the earth, and is the level most representative of the air flow in the lower atmosphere immediately above the layer affected by surface friction. This level is free of local wind and topographic effects (such as sea breezes, downslope winds etc) and it is commonly defined atop the atmospheric boundary layer (ABL).

For the gradient winds there is no balance between the Coriolis force and the Pressure gradient force (as this is the case for geostrophic winds), resulting in a non-zero net force F_{net} known as the Centripetal force. This F_{net} is what causes the wind to continually change direction as it goes around a circle as shown in figures 1 and 2 (Stull 2017). By describing this change in direction as causing an apparent force (Centrifugal), we can find the equation for the gradient wind. Equation 6.1 defines the steady-state gradient wind and represents the balance of the Pressure Gradient Force (F_{PG}), Centrifugal $(F_{CN} = -F_{net})$ and Coriolis (F_{CF}) forces at the gradient level (figures 1 and 2):

$$\underbrace{V_g^2(r)}_{F_{CN}\,\text{term}} + \underbrace{frV_g(r)}_{F_{CF}\,\text{term}} - \underbrace{\frac{r}{\rho_{air}}\frac{\partial P(r)}{\partial r}}_{F_{PG}\,\text{term}} = 0 \tag{6.1}$$

where: $V_g(r)$ is the gradient level wind speed at radius r, $P(r)$ is the pressure at radius r, r is the radial distance, $f = 2\Omega\sin\phi$ is the Coriolis parameter, $\Omega = 7.27221\cdot10^{-5}s^{-1}$ is the rotational speed of the earth, ϕ is the latitude in radians and ρ_{air} is the air density (assumed constant: $1.15\,kg/m^3$). The quadratic equation 6.1 has two roots:

$$V_g(r) = \sqrt{\frac{r}{\rho_{air}}\frac{\partial P(r)}{\partial r} + \left(\frac{rf}{2}\right)^2} - \frac{rf}{2} \tag{6.2}$$

$$V_g(r) = -\sqrt{\frac{r}{\rho_{air}}\frac{\partial P(r)}{\partial r} + \left(\frac{rf}{2}\right)^2} - \frac{rf}{2} \tag{6.3}$$

where equation 6.2 is the solution for $V_g(r)$ for flow around a cyclone that is, around a low pressure (figure 1) while, equation 6.3 represents the solution for $V_g(r)$ for flow around an anticyclone that is, around a high pressure (figure 2).

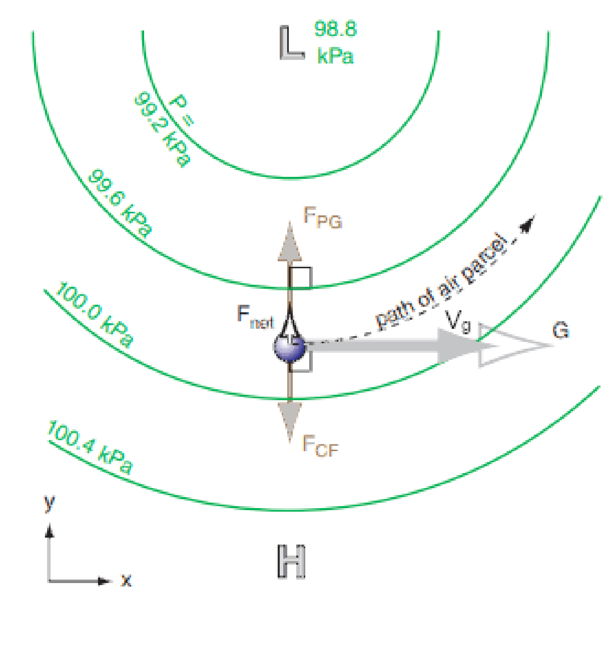


Figure 1: Forces that cause the gradient wind to be faster than geostrophic for an air parcel circling around a low-pressure center (a **cyclone** in N. Hemisphere). The centrifugal force pulls the air parcel inward to force the wind direction to change as needed for the wind to turn along a circular path. Source↩ : Practical Meteorology: An Algebra-based Survey of Atmospheric Science. Roland Stull, The University of British Columbia, Vancouver, Canada.

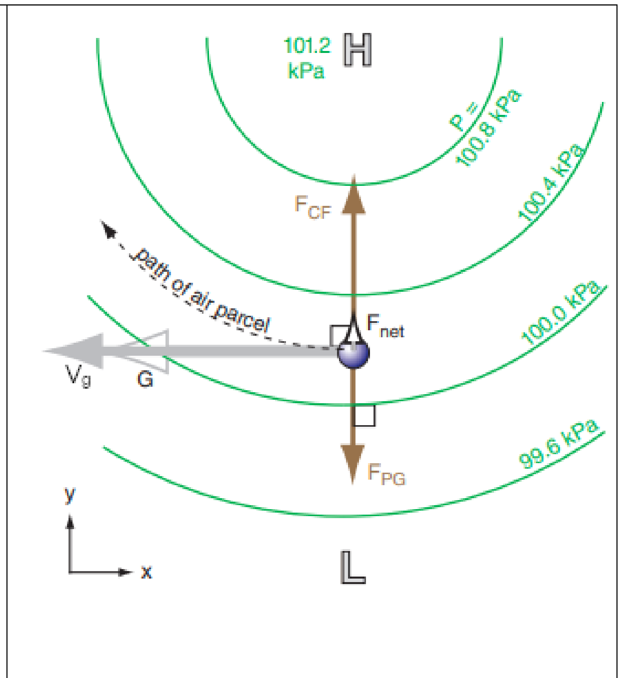


Figure 2: Forces that cause the gradient wind to be faster than geostrophic for an air parcel circling around a high-pressure center (an **anticyclone** in the N. Hemisphere). The centrifugal force pulls the air parcel inward to force the wind direction to change as needed for the wind to turn along a circular path. Source: Practical Meteorology: An Algebra-based Survey of Atmospheric Science. Roland Stull, The University of British Columbia, Vancouver, Canada.

To derive the analytical expression for $V_g(r)$, HM80 assumed a surface pressure profile that is approximated by the following hyperbolic equation:

$$P(r) = P_c + (P_n - P_c)e^{-A/r^B} \tag{6.4}$$

where: A, B are scaling parameters, $P(r)$ is the pressure at radius r, P_n is the ambient pressure (assumed constant: $1013.25\,mbar$) and P_c is the central pressure. Substituting the expression for $P(r)$ into equation 6.2 and, the following expression for the wind speed at the gradient level is obtained:

$$V_g(r) = \sqrt{AB(P_n - P_c)e^{-A/r^B}/\rho_{air}r^B + (\frac{rf}{2})^2} - \frac{rf}{2} \tag{6.5}$$

To determine the scaling parameters A and B, it is assumed that at the region of the radius of maximum winds (RMW) that is, at the region of the sustained maximum wind speeds ($r = R_{max} =$ RMW), the wind speed V_g satisfies the first of equations 6.6. It is also assumed that the Rossby number R_o is very large (the third of equations 6.6), so that the Coriolis forces can be neglected and therefore the air is in cyclostrophic balance (Holland 1980) as described by equation 6.7 for the cyclostrophic wind speed $V_c(r)$.

$$V_g = V_{max}\,; \quad \frac{dV_g}{dr} = 0\,; \quad R_o = \frac{V_{max}}{fR_{max}} \gg 1 \tag{6.6}$$

$$V_c(r) = V_g(r)\Big|_{r \to R_{max}} = \sqrt{AB(P_n - P_c)e^{-A/r^B}/\rho_{air}r^B} \tag{6.7}$$

Applying the second of the conditions in equations 6.6 on equation 6.7, we find that the radius of maximum winds is independent of the relative values of the ambient and the central pressure and it is defined only by the scaling parameters A and B as: $R_{max} = A^{1/B}$, or $A = R_{max}^B$. Substituting the expression for A into equation 6.7 and setting $V_c(R_{max}) = V_{max}$, the expression for the scaling parameter B (widely known as the Holland B parameter) is readily determined:

$$A = R_{max}^B\,; \quad B = \frac{\rho_{air}eV_{max}^2}{P_n - P_c} \tag{6.8}$$

Physically, the Holland parameter B defines the shape of the pressure profile (equation 6.4) while, the parameter A determines its location relative to the origin (Holland 1980). HM80 states that plausible ranges of B would be between 1 and 2.5 to to limit the shape and size of the vortex. Based on equations 6.4, 6.5 and 6.8, and re-organizing the pressure and the gradient wind speed equations, the final equations of the HM80 parametric TC model that *PAHM* solves are summarized as follows:

$$B = \frac{\rho_{air}eV_{max}^2}{P_n - P_c} \tag{6.9}$$

$$P(r) = P_c + (P_n - P_c)\cdot e^{-(R_{max}/r)^B} \tag{6.10}$$

$$V_g(r) = \sqrt{V_{max}^2 \cdot \Big(\frac{R_{max}}{r}\Big)^B \cdot e^{1-(R_{max}/r)^B} + \Big(\frac{rf}{2}\Big)^2} - \frac{rf}{2} \tag{6.11}$$

As reasoned in (Gao 2018), a large R_o ($\mathcal{O}(10^3)$) describes a system in cyclostrophic balance dominated by inertial and centrifugal forces with negligible Coriolis force (e.g., a tornado or the inner core of an intense hurricane), while a small value R_o $(10^{-2} \sim 10^2)$ describes a system in geostrophic balance strongly influenced by the Coriolis force (e.g., the outer region of a TC). Therefore, the cyclostrophic balance assumption made in HM80 is only valid for describing an intense but narrow TC with a large R_o, and not suitable for weak but broad tropical cyclones with small R_o values. Although this is a limitation of the HM80 model, equations 6.9 through 6.11, are widely used in hurricane risk studies and storm surge studies due to their simplicitly and their capability to generate the atmospheric fields quickly and efficiently.

6.2 Generalized Asymmetric Vortex Holland model (*GAHM*)

The Generalized Asymmetric Vortex Holland model (Gao 2018 and Gao 2015) extends HM80 by eliminating the cyclostrophic assumption at the the region of RMW (the third of equations 6.6) to allow the generation of representative wind fields for a wider range of TCs. *GAHM* also introduces a composite wind methodology to fully use all multiple storm isotachs in TC forecast or best track data files to account for asymmetric tropical cyclones such as a land-falling hurricane.

GAHM model solves the gradient wind equation for V_g (equation 6.2) by eliminating the influence of the Rossby number (R_o)) on the gradient wind solution assuming that:

$$V_g = V_{max}\,; \qquad \frac{dV_g}{dr} = 0 \tag{6.12}$$

The pressure profile used is the same as in HM80 (equation 6.4) where the scaling parameter A is slightly re-defined by introducing a new scaling factor (ϕ) : $\phi = A/R_{max}^B$, or $A = \phi R_{max}^B$. Substituting the expression for A into equation 6.5 and using the second of equations 6.12, an adjusted Holland B parameter (B_g), is derived as:

$$B_g = \frac{(V_{max}^2 + fV_{max}R_{max})\rho_{air}e^{\phi}}{\phi(P_n - P_c)} = B\frac{(1 + 1/R_o)e^{\phi-1}}{\phi}\,; \qquad B = \frac{\rho_{air}eV_{max}^2}{P_n - P_c} \tag{6.13}$$

Substituting the expressions for A and B (replaced by B_g) into equation 6.5 and using the first of equations 6.12, the final expression for the scaling parameter ϕ is derived:

$$\phi = \frac{1 + fV_{max}R_{max}}{B_g(V_{max}^2 + fV_{max}R_{max})} = 1 + \frac{1/R_o}{B_g(1 + 1/R_o)} \tag{6.14}$$

Based on equations 6.4, 6.5, 6.13, and 6.14 and re-organizing the pressure and the gradient wind speed equations, the final equations of the *GAHM* parametric TC model that *PAHM* solves are summarized as follows:

$$B_g = B\big(1 + \frac{1}{R_o}\big)^{e^{-\phi}/\phi}\,; \quad \phi = 1 + \frac{1/R_o}{B_g(1 + 1/R_o)}\,; \quad B = \frac{\rho_{air}eV_{max}^2}{P_n - P_c}\,; \quad \text{and} \quad R_o = \frac{V_{max}}{fR_{max}} \tag{6.15}$$

$$P(r) = P_c + (P_n - P_c)\cdot e^{-\phi(R_{max}/r)^{B_g}} \tag{6.16}$$

$$V_g(r) = \sqrt{V_{max}^2\cdot\big(\frac{R_{max}}{r}\big)^{B_g}\cdot(1 + 1/R_o)\cdot e^{\phi(1-(R_{max}/r)^{B_g})} + \big(\frac{rf}{2}\big)^2} - \frac{rf}{2} \tag{6.17}$$

Given the values for V_{max}, R_{max}, P_n and P_c, the iterative solution of the first two of equations 6.15 produces the final values of B_g and ϕ.

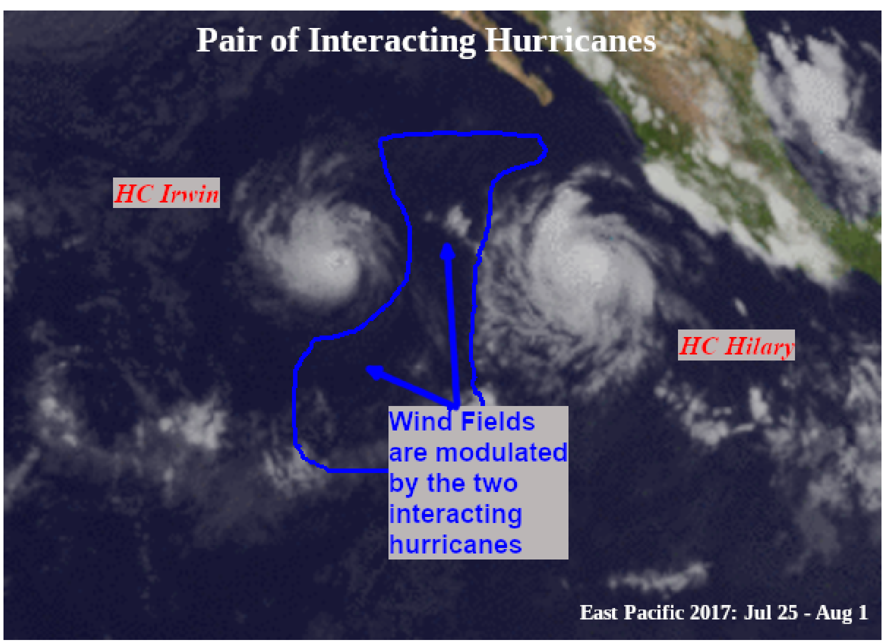
Chapter 7

PaHM Features and Capabilities

7.1 Data Input Interfaces

7.2 Model Grids

7.3 Modeling Multiple Interacting Storms



7.4 Coupling Environment

Chapter 8

Model Application and Implementation Technology

8.1 Standalone Model Application

8.2 Coupled Model Application

Chapter 9

Model Evaluation

In this section the developed modeling system and its associated modeling components are evaluated under realistic atmospheric and ocean conditions, varied flow domains and coupling configurations so the performance of *PaHM* can be analyzed. Although the individual modeling components of *PaHM* have been evaluated, the overall model performance still needs evaluation and verification. Switching on and off the different modeling components shows the relative performance of each modeling component with respect to each other and to the problem being investigated. *PaHM*'s outputs are: (*a*) 10-m wind speed, (*b*) wind direction and (*c*) atmospheric pressure reduced to mean sea level (*MSLP*).

9.1 Statistical Performance Measures

Only parametric statistical tests are used in the performance evaluation of the developed model that include (*a*) the mean (*m*) of the differences between the calculated and the measured or observed data sets, (*b*) the standard deviation (*SD*), (*c*) the root mean square differense (*RMSE*), (*d*) the coefficient of determination (R^2), (*e*) the bias (*bias*), (*f*) the scatter coefficient (*SI*), (*g*) the Willmott (2012) skill (*WS12*) and (*h*) the Nash and Sutcliff (1970) skill (*NS*).

a) Mean: The mean of the differences between the modeled and measured data provides a gross overall measure of the model performance and is calculated as:

$$m = \frac{\sum_{i=1}^{n} \left(M_i - O_i \right)}{n} \tag{9.1}$$

where n is the total number of observation or modeled points, M_i are the modeled and O_i are the observed values of each evaluated variable. The smaller the mean difference the better the agreement between the model and the observed values, with a value of zero denoting absolute agreement.

b) Standard Deviation: The standard deviation (*SD*) is a measure of the distance of the difference between the calculated and observed data from the mean difference. Small standard deviations indicate that the differences are closer to the mean. The standard deviation is calculated as:

$$SD = \sqrt{\frac{\sum_{i=1}^{n} \left[\left(M_i - O_i \right) - m \right]^2}{n}} \tag{9.2}$$

c) Root Mean Square Differense: The root mean square difference (*RMSE*) is another test of the overall model performance that measures how close the modeled value of a variable is to the observed value. Mathematically, the test is defined as:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} \left(M_i - O_i \right)^2}{n}} \tag{9.3}$$

The differences between the modeled and observed data are squared so that more weight is given to larger errors.

d) Coefficient of Determination: The coefficient of determination R^2, where R is the correlation coefficient, indicates the proportion of the variance in the dependent variable that is predicted by linear regression and the independent variable. In general, a high R^2 value indicates that the model is a good fit for the data. An $R^2 = 0.62$, indicates that 62% of the variation in the outcome has been explained. A value of 1 would indicate that the regression line represents all of the data (the best fit) while, a value of 0 shows no association at all. Note that the coefficient of determination shows only the magnitude of the association, not whether that association is statistically significant.

$$R = \frac{\sum_{i=1}^{n} \left(O_i - \overline{O} \right) \left(M_i - \overline{M} \right)}{\sqrt{\sum_{i=1}^{n} \left(O_i - \overline{O} \right)^2 \left(M_i - \overline{M} \right)^2}} \tag{9.4}$$

where: $\overline{M} = (1/n) \sum_{i=1}^{n} M_i$ is the mean of the modeled values and $\overline{O} = (1/n) \sum_{i=1}^{n} O_i$ is the mean of the observation values.

e) Model Bias: Bias is the tendency of a statistical estimator to overestimate or underestimate a parameter. The bias of a statistical estimator is the difference between the expected value of the statistic and the true value of the sample (population) parameter. If the bias is close to zero then the statistical estimator is an unbiased estimator, otherwise it is considered a biased estimator. The statistical estimator used here is the sample or population mean.

$$bias = \overline{O} - \overline{M} \tag{9.5}$$

f) Scatter Index: The scatter index (*SI*) is calculated by dividing the *RMSE* with the mean of the observations and multiplying it by 100 (percent):

$$SI = \frac{RMSE}{\overline{O}} \tag{9.6}$$

where *SI* is the percentage of *RMSE* with respect to the mean of the observations that is, the percentage of expected error for the parameter.

g) Willmott Skill Index: The evaluation of model performance, that is the comparison model estimates with observed values, is a fundamental step for model development and use. This validation process includes criteria that rely on mathematical measurements of how well model results simulate the observed values. The parameter (*WS12*), called index of agreement, is a relative average error and bounded measure. The best agreement between model results and observations will yield a skill of one while, a value of ≤ 0 denotes a complete disagreement. This statistic is calculated using the following equations:

$$\left.\begin{array}{l} SM1 = \sum_{i=1}^{n} \left|O_i - M_i\right| \;\; ; \;\; SM2 = \sum_{i=1}^{n} \left|M_i - \overline{O}\right| \left|O_i - \overline{O}\right| \\ WS12 = 1.0 - SM1/(2.0 \cdot SM2) \quad \text{for} \quad SM1 \leq 2.0 \cdot SM2 \\ WS12 = 2.0 \cdot SM2/SM1 - 1.0 \quad \text{for} \quad SM1 > 2.0 \cdot SM2 \end{array}\right\} \tag{9.7}$$

The range of qualification for the Willmott's skill index is given in the following table:

$$\left.\begin{array}{rr} 0.8 < WS12 \leq 1.0 & \text{Excellent} \\ 0.6 < WS12 \leq 0.8 & \text{Good} \\ 0.3 < WS12 \leq 0.6 & \text{Reasonable} \\ 0.0 < WS12 \leq 0.3 & \text{Poor} \\ WS12 \leq 0.0 & \text{Bad} \end{array}\right\} \tag{9.8}$$

h) Nash and Sutcliff Skill Index: The Nash and Sutcliff skill index is similar to the Willmott's skill index and it is calculated as:

$$NS = 1.0 - \frac{\sum_{i=1}^{n} \left(M_i - O_i\right)^2}{\sum_{i=1}^{n} \left(O_i - \overline{M}\right)^2} \tag{9.9}$$

For a perfect model with an estimation error variance equal to zero, the Nash and Sutcliffe index equals 1. Values of the Nash and Sutcliffe index close to 1, suggest a model with more predictive skill. The range of qualification presented in the case of the Willmott's skill index can be used for the Nash and Sutcliff skill index case as well.

All the above tests give information on the size, but not of the nature of the error, which make them adequate measures for a preliminary model evaluation. However, a deeper analysis might require specific tests that can reveal the nature of the errors and help with future model improvements.

9.2 Hurricane Florence (2018) Case Study

Link to the picture: Figure [1]

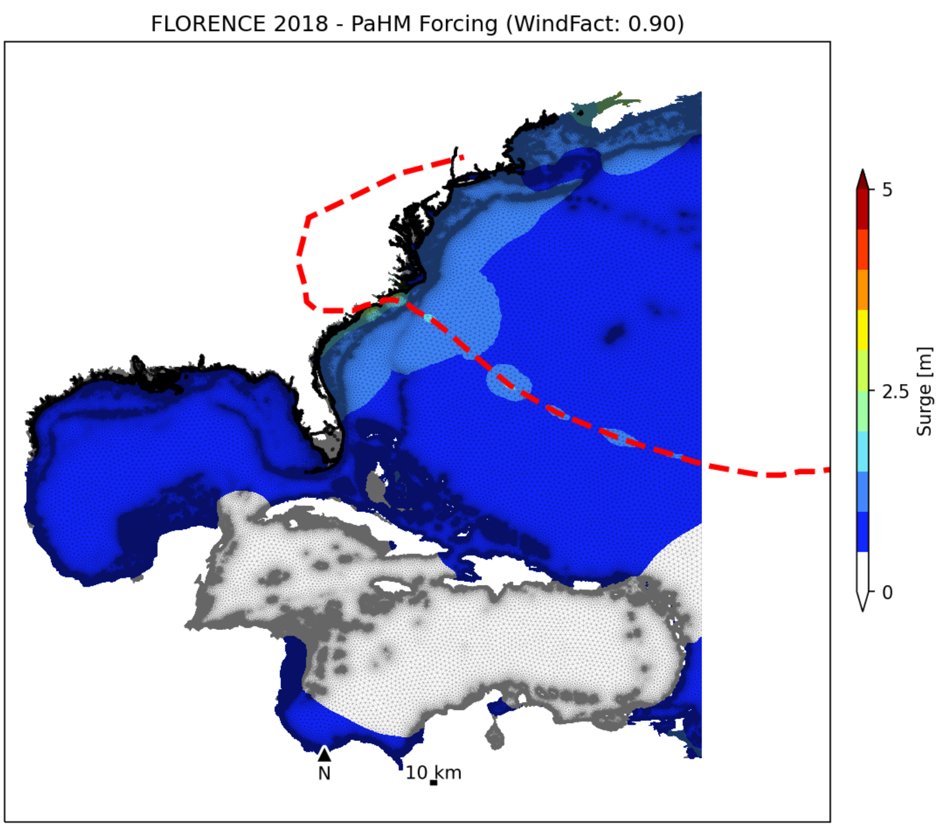


Figure 9.1 Figure 1:

9.2.1 Standalone Model Evaluation

9.2.1.1 Model Results and Discussion

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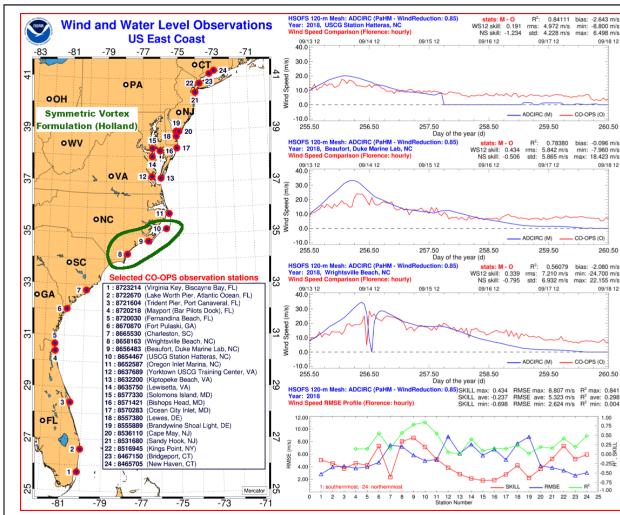
<td>
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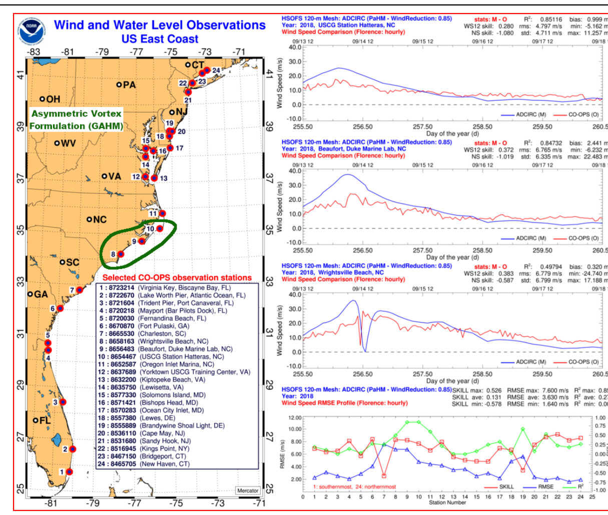
<td>
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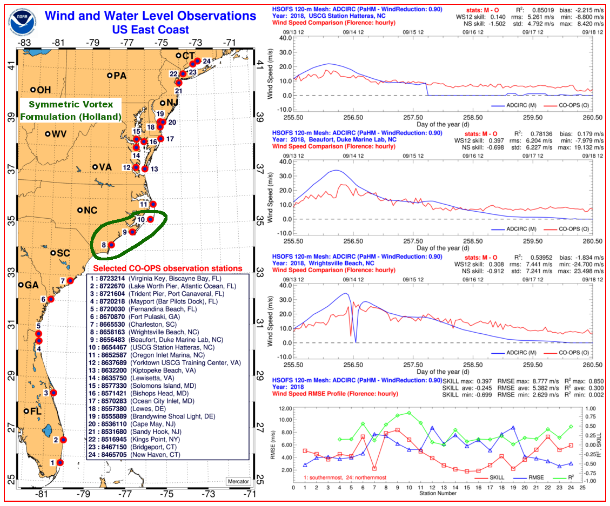
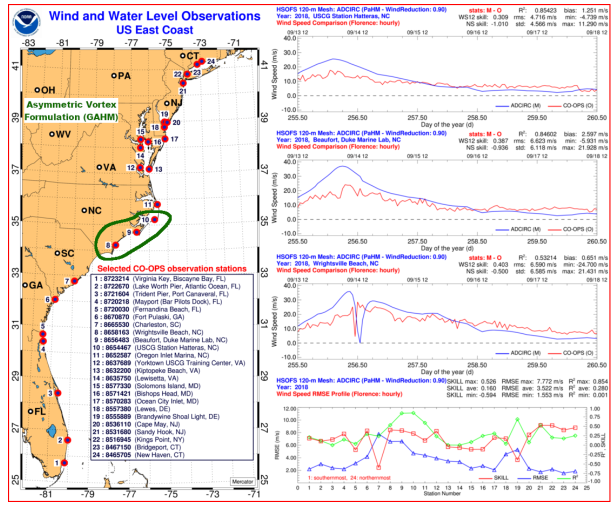
Table 9.2 Caption Text





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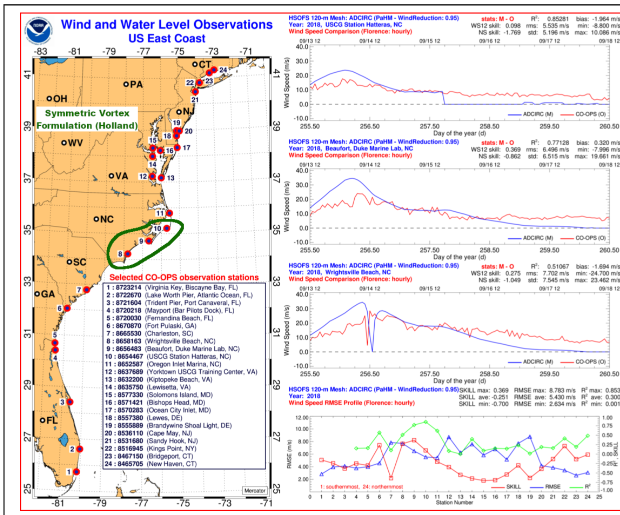
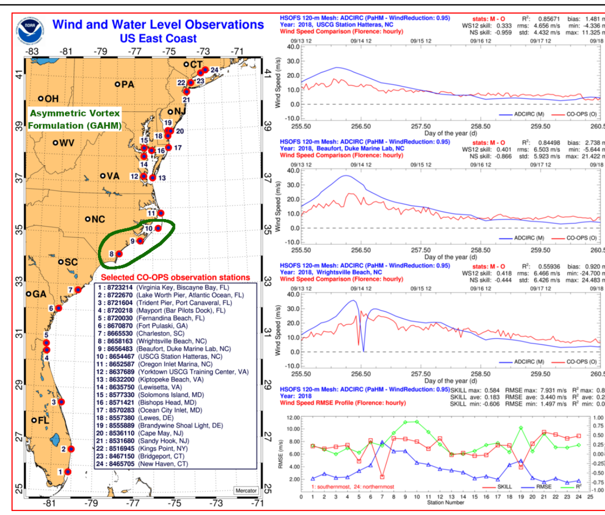
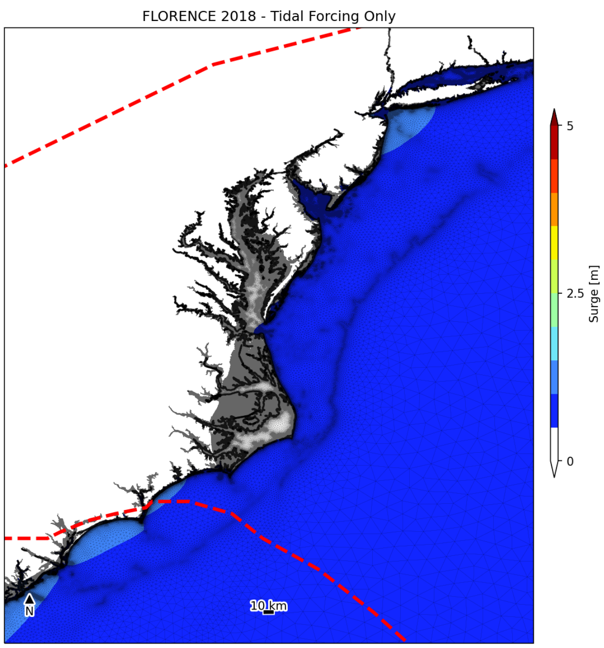
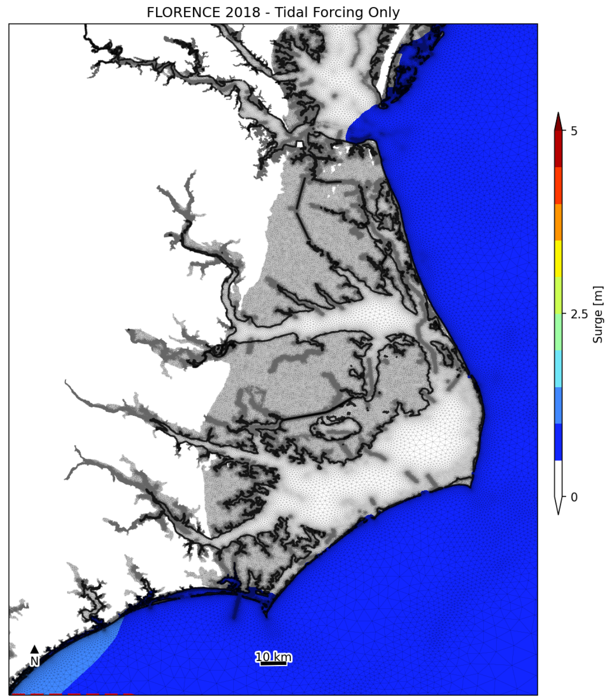




9.2.2 Coupled Model Evaluation

The coupled modeling approach described here allows to address the impacts of extreme storm events such as hurricanes on coastal areas. The HSOFS modeling system is applied and evaluated for Hurricane Florence on the Eastern coast of the US that includes the important basins of Delaware Bay, Chesapeake Bay and the Carolinas. While individual modeling components (ADCIRC, WAVEWATCH III) have already been evaluated successfully using standard statistical measures, PAHM is currently evaluated as part of the overall HSOFS evaluation. Initial HSOFS simulations show promising results on predicting total water level and flood inundation.

Table 9.4 Caption Text

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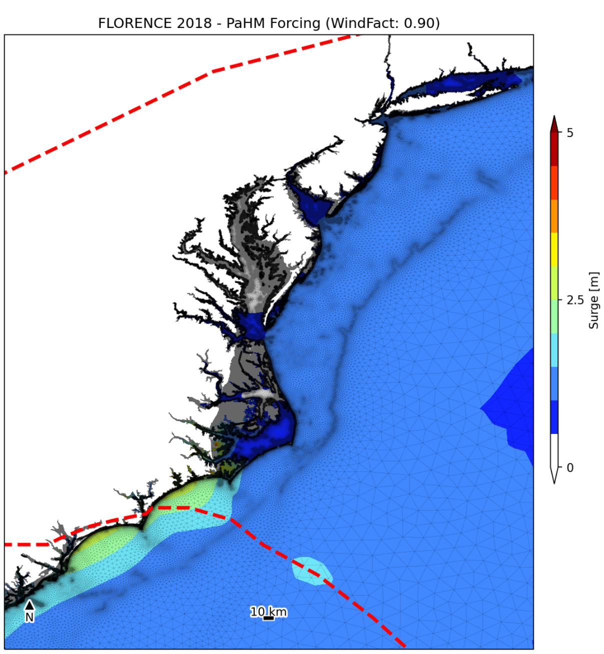	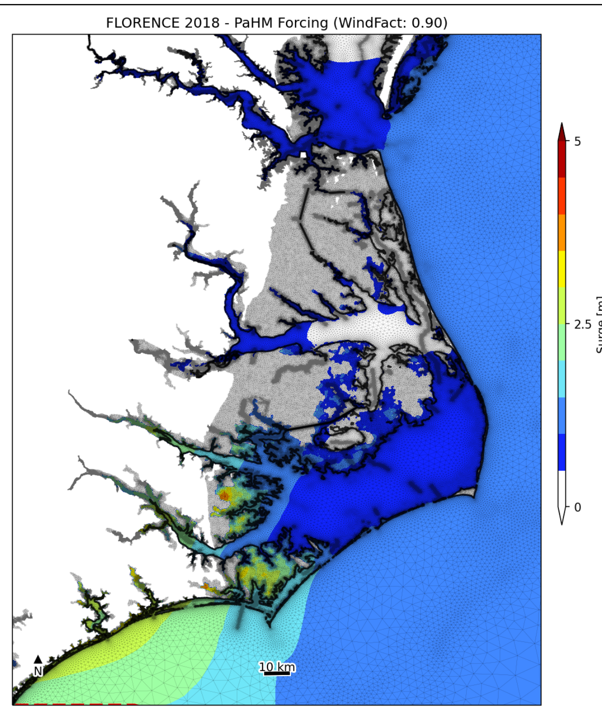

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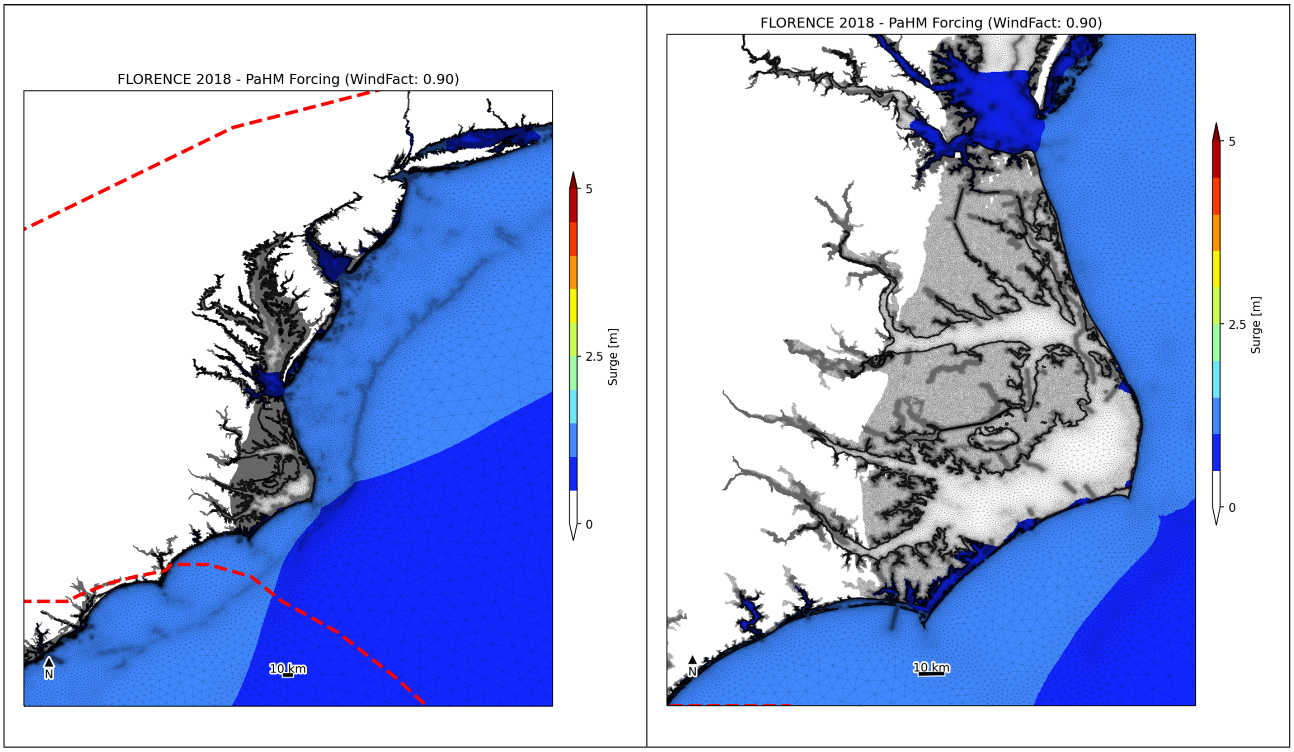
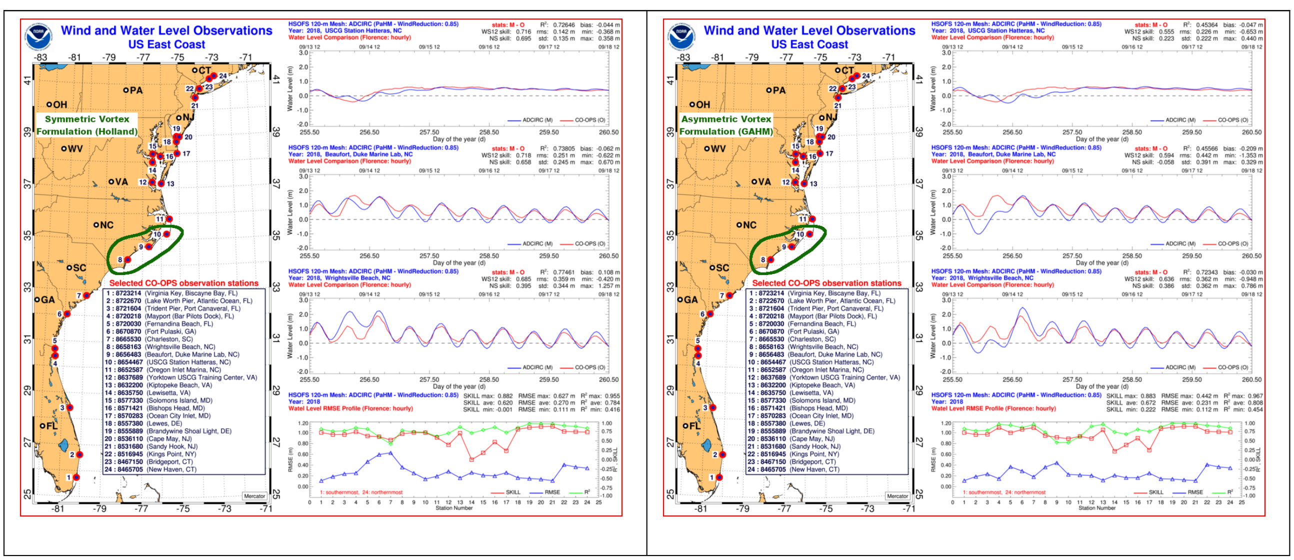


9.2.2.1 Coupled Model Results and Discussion

Table 9.7 Caption Text



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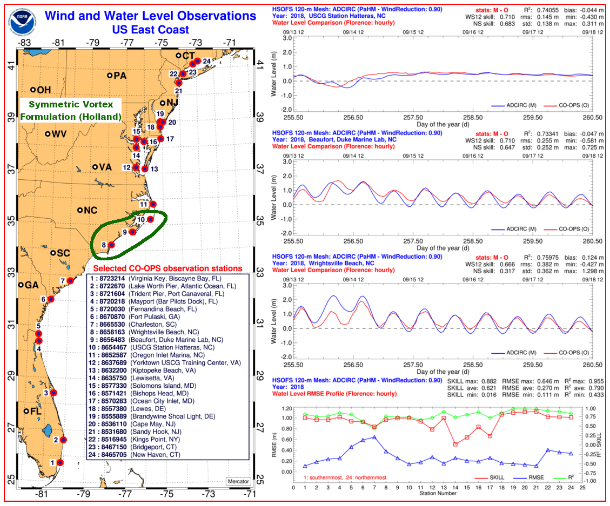

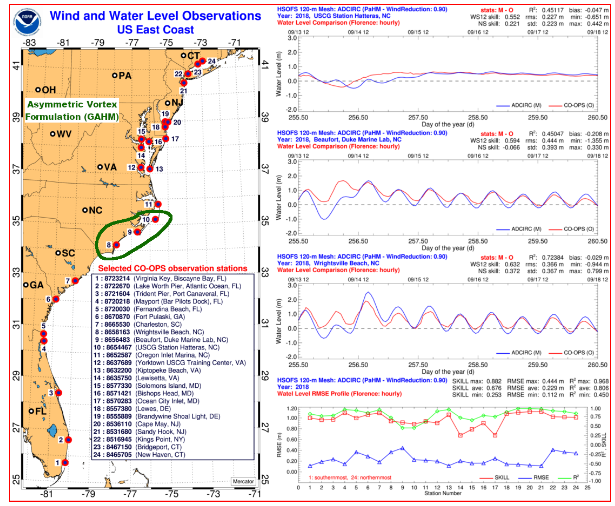

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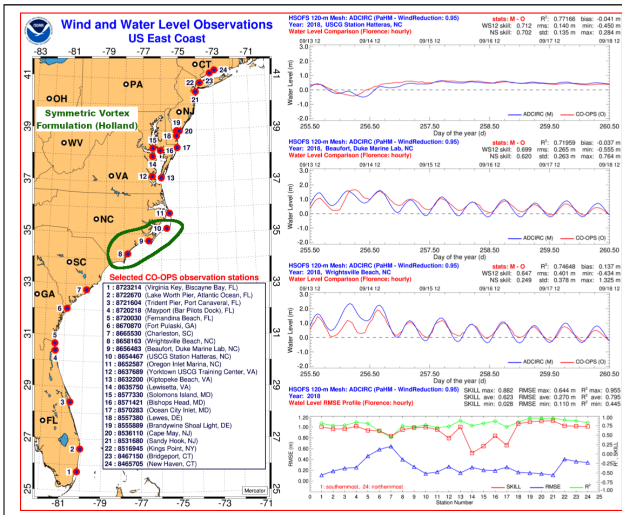

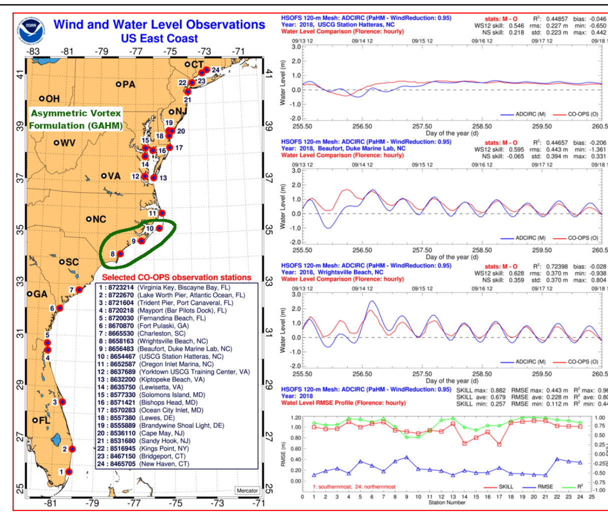

9.3 Conclusions

Chapter 10

List of Deliverables

Chapter 11

Glossary

Chapter 12

Credits

Chapter 13

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