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The HRD real-time hurricane wind analysis system

Mark D. Powell*, Sam H. Houston, Luis R. Amat, Nirva Morisseau-Leroy

NOAA/AOML Hurricane Research Division, 4301 Rickenbacker Cswy, Miami, FL 33149, USA

Abstract

The HRD real-time wind analysis system is currently undergoing evaluation in the operational forecasting environment of the National Hurricane Center. The system is an object-oriented, distributed, three-tiered client–server application that assimilates disparate observations and processes the data into a common framework for exposure, height and averaging time. The data are then examined collectively or by type, quality controlled and passed on to a scale-controlled objective analysis algorithm. Several products are derived from the analysis wind field and storm track, yielding effective tools for disaster assessment, emergency management, and recovery. Published by Elsevier Science Ltd.

Keywords: Hurricanes; Tropical cyclones; Emergency management; Data assimilation; Disaster mitigation

1. Introduction

Timely evacuations and preparations before hurricane landfall help to save lives and property but losses are inevitable even with perfect forecasts. Mitigating a portion of such losses may be possible by effective use of meteorological observations analyzed during and after the event. Real-time analyses of measurements gathered from reconnaissance aircraft, land, marine, and space observation platforms serve as guidance to help meteorologists determine storm intensity and the extent of damaging winds contained in hurricane forecasts and warnings. During landfall of a tropical cyclone, detailed analyses coupled with geographic information help to identify communities experiencing the most severe winds and storm surge. Timely information on the actual areas impacted by a hurricane's eyewall and strongest winds should assist emergency managers by minimizing confusion and assisting search and rescue and recovery at the earliest stages following a disaster. In addition to the operational

* Corresponding author. E-mail: powell@aoml.noaa.gov.

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needs for such information, many segments of the commercial, scientific and government user community have expressed interest in obtaining access to hurricane wind field data in a graphical or gridded format for research and decision-making purposes.

The National Oceanic and Atmospheric Administration's (NOAA) Hurricane Research Division (HRD) maintains an annual hurricane field program that has resulted in published investigations of several hurricanes including Frederic (1979), Alicia (1983), Hugo (1989), and Andrew (1992) [1–5]. These studies have contributed to a standardized method for wind analysis using methods drawn from wind engineering and micrometeorology [4]. This method is consistent with that used by NOAA's National Hurricane Center (NHC), and is readily converted to wind load frameworks used in building codes by using gust factors.

Analyses are produced by compositing all available observations relative to the storm center. Observations include Air Force and NOAA aircraft, ships, buoys, C-MAN platforms, and surface airways. All data are quality controlled and then processed to conform to a common framework for height (10 m), exposure (marine or open terrain over land), and averaging period (maximum sustained 1 min wind speed). Several hours of observations are usually required to provide sufficient data density and coverage for an analysis. An analysis domain consists of at least three nested meshes within which the scale of resolvable features can be controlled [6]. The resulting objective analysis is representative of the mean state of the storm during the chosen time period and a typical 10 h reconnaissance mission will yield 2–3 analyses. The primary analysis product is a streamline and isotach contour plot for a given mesh and is designed to convey the location and strength of the maximum wind as well as the extent of hurricane force, 50 kt, and/or gale force winds. Most of the real-time analyses represent marine exposures. At landfall, land exposure analyses are conducted based on buoy, C-MAN, surface airways, and surface-adjusted reconnaissance observations converted to open terrain; these analyses are considered preliminary until sufficient field exposure examinations are conducted to allow integration of land-based anemometer observations.

2. Wind analysis distributed application (WAnDA)

HRD has been producing real-time analyses of tropical cyclone surface wind observations on an experimental basis since 1993 [7]. WAnDA, whose initial implementation saw extended use during the 1996 hurricane season, is an object-oriented (OO) software product written in Objective-C utilizing the NeXTSTEP user and development platform. Currently, the application engine first fetches data from a flat-file database, the data are then processed, quality controlled, and passed on to the analysis server, and then displayed on an application server as graphical products that are fixed or hard copied to the clients. During the 1995 hurricane season, 86 real-time analyses were produced. With partial automation of the analysis process, that number rose to 134 analyses in 1996.

The trend in the last decade in software development has been to model the real world through the OO paradigm. Through the use of abstract data types and data encapsulation within classes of objects, objects represented in software send and receive messages to each other that are meaningful to them via "publicly visible" interfaces. Developing software in this manner helps programmers and designers alike by allowing the creation of intricately dynamic software with potentially reusable and modular code.

WAnDA employs a synoptic or storm-relative view (Fig. 1) of atmospheric and oceanographic observations. The synoptic view is advantageous for study of large-scale weather systems at a particular instance in time. The storm-relative view converts observations to a range and bearing relative to the storm over a time period during which the storm is considered to be near steady state; geography is then positioned relative to the storm location at a particular time. The storm-relative view is advantageous for filling data void areas. WAnDA is broken up into three subsystems (Fig. 2): (1) Quality control, (2) analysis automation, and (3) output generation. A subsystem groups tightly coupled classes of objects, such as those whose object instances frequently interact with each other, together so that the classes can be viewed as a single entity. The graphically oriented quality control (QC) subsystem is part of WAnDA's front end and resides and runs on the client workstation. A QC session involves selecting desired observation types to be viewed (Fig. 3a), and determining a storm-track-based time window for viewing the data (Fig. 3b). All observations of the selected type are then plotted in the storm-relative view for the chosen time window and geography is positioned for the center time (Fig. 3c). Decisions are made about data validity through visual nearest-neighbor comparison and inspection. QC provides the user with zooming, distance and data inspection tools (Fig. 3d) to facilitate the task of selecting an acceptable set of data from the plot window. Once the data are quality controlled, they are passed, along with a storm track, through a series of Analysis Automation subsystem components. Each component is distributed over two machines, a NeXTSTEP client and a VAX/VMS

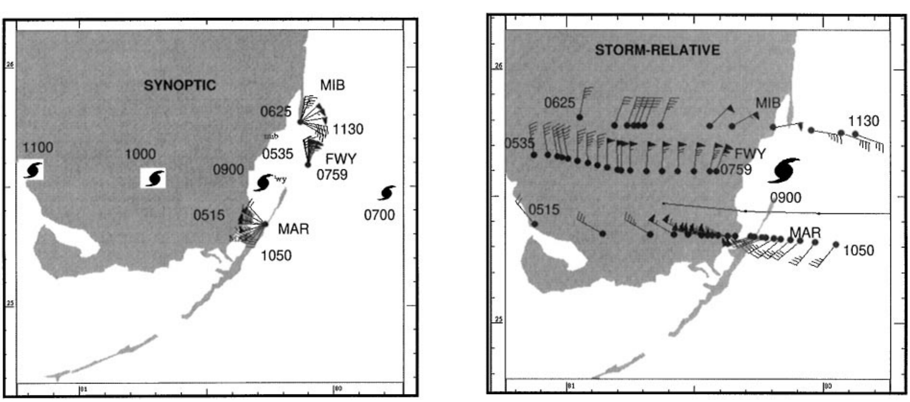

Fig. 1. Comparison of synoptic (L) and storm-relative (R) views of Hurricane Andrew observations (times given in UTC) at Fowey Rocks (FWY), Miami Beach (MIB), and yacht Mara Cu (MAR). Hurricane symbol represents storm center positions at the indicated times (UTC).

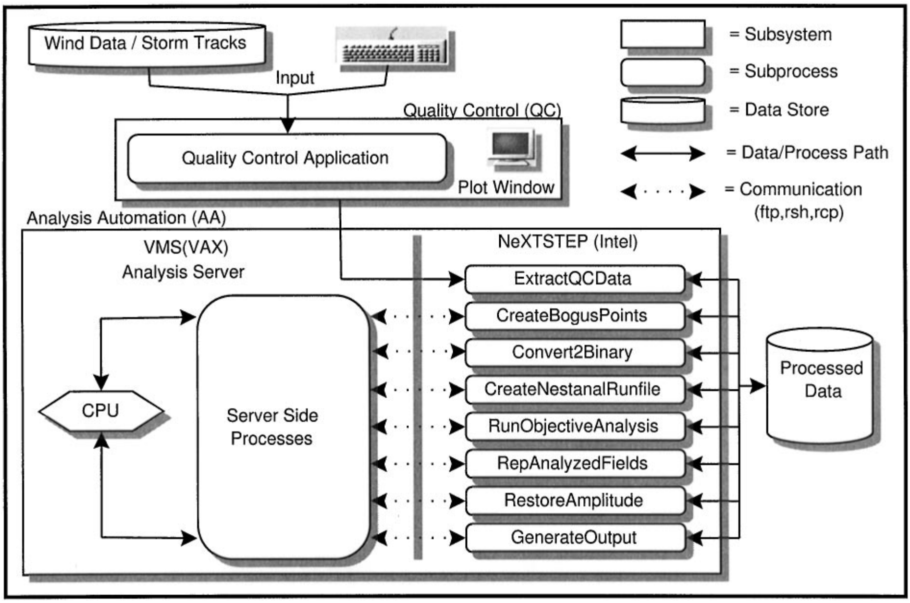

Fig. 2. Process and data flow diagram for WAnDA.

server where the analysis processes reside. WAnDA uses state machine engines to orchestrate all of the state transitions involved in the analysis automation. Included in this automation is the automatic archival of all steps of an analysis for research purposes; any analysis can be traced back to its component processes and data set. The output generation subsystem creates a graphical representation of the wind fields. Output generation relies on an in house graphics package to display an analysis on the client screen where it can then be annotated and saved to an encapsulated postscript document. The graphical analysis document can then be printed or transmitted electronically to the client (see next section) for use as guidance by NHC forecasters preparing hurricane and tropical storm warnings and advisories.

3. Evaluation of the HRD wind analysis system during Hurricane Fran

Hurricane Fran killed 34 and damaged 3.2 billion in property after making landfall near Cape Fear, North Carolina on 6 September 1996 [8]. Much of the property loss was due to storm surge and waves along the coast. During Fran's lifetime, 27 HRD wind analyses were provided to NHC forecasters in real-time (Fig. 4). Analyses were delivered according to a schedule consistent with NHC's forecast and warning cycle (Fig. 5), which required analyses to be available at least 30 min before scheduled coordination calls with National Weather Service forecast offices and emergency managers. A real-time, marine exposure analysis of wind observations from

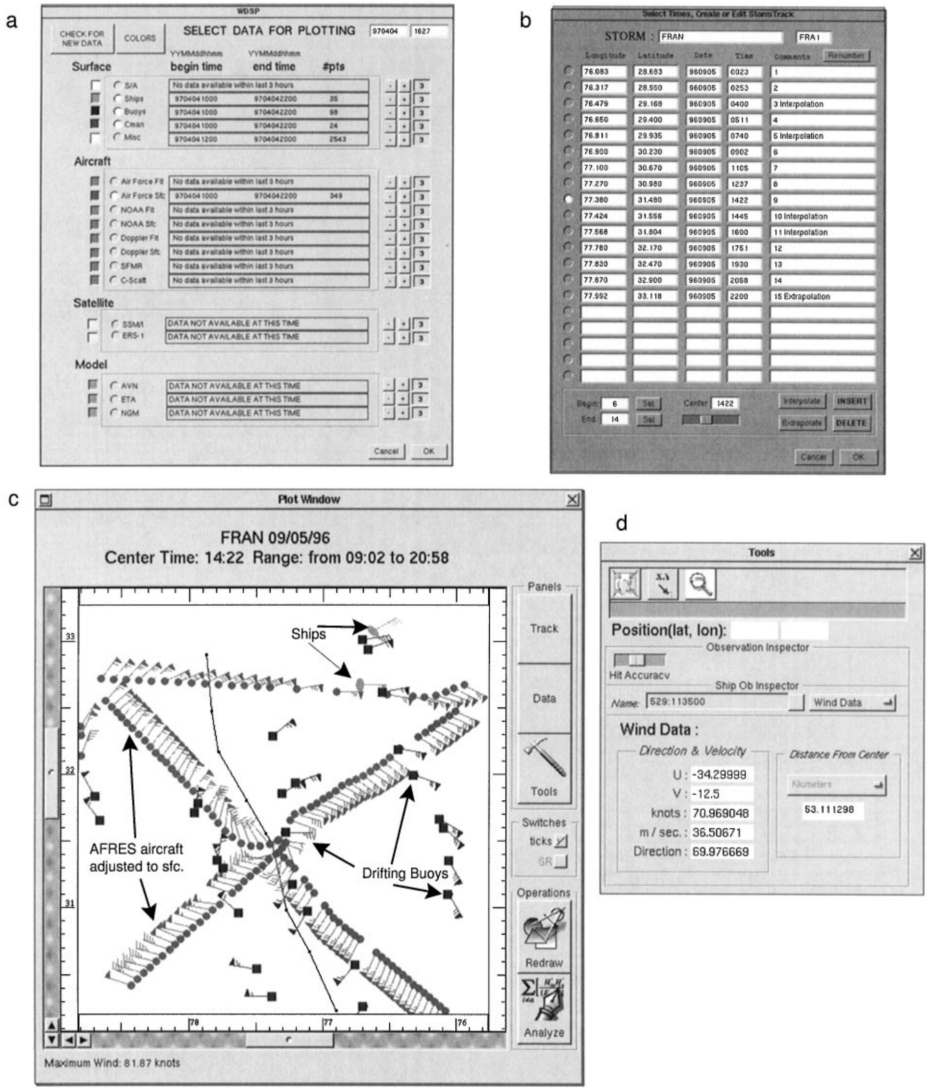

Fig. 3. WAnDA user interface elements. (a) Data type selection panel, (b) storm track panel, (c) quality control window displaying Hurricane Fran observations, (d) inspector tool used to examine individual datum.

air-dropped drifting buoy arrays, moored buoys, C-MAN stations and surface-adjusted flight-level observations from the Air Force Reserves (AFRES) C-130 research air-craft (using data depicted in Fig. 3c) is shown in Fig. 6 for 1900 UTC, 5 September (about 5 h before landfall). Real-time analyses presented to NHC for guidance in marine advisories use knots for wind speed units; metric units are not yet employed operationally.

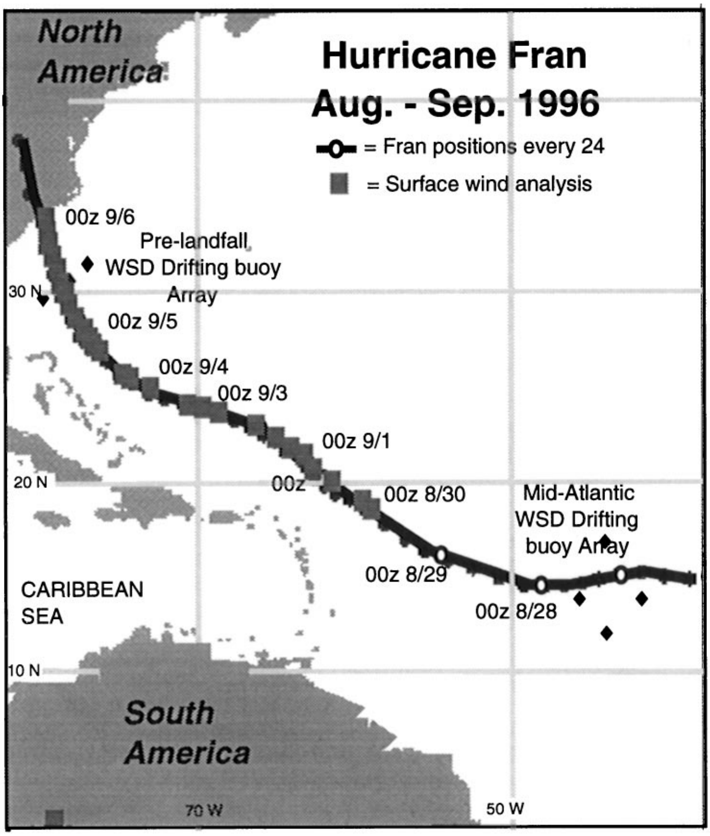

Fig. 4. Track of Hurricane Fran showing positions of real-time surface wind analyses and locations of air-dropped drifting buoys.

After a hurricane makes landfall, HRD seeks supplemental wind observations and documentation of instruments and site exposures. Poststorm hurricane analyses are conducted to determine the wind distribution at landfall and inland and to validate decay models such as the HRD Inland Wind Model [9] currently used by FEMA. Anemometer site documentation is especially important for determining inland wind fields. Final poststorm analyses are typically delayed several months to accommodate site visits to document anemometer heights and exposures. In Hurricane Andrew, closely spaced raw wind observations were shown [4] to differ by 40–50%, but consideration of height and exposure significantly reduced spatial variance in the wind field resulting in accuracies estimated $\sim 10\%$. Exposure documentation of all operational ASOS, aviation route (METAR), and C-MAN anemometer sites in hurricane prone areas is required to reach the goal of analyzing the surface wind field over land in real-time during landfall and inland. The authors are initiating an effort to document exposures at automatic weather stations from Texas to Maine. If the

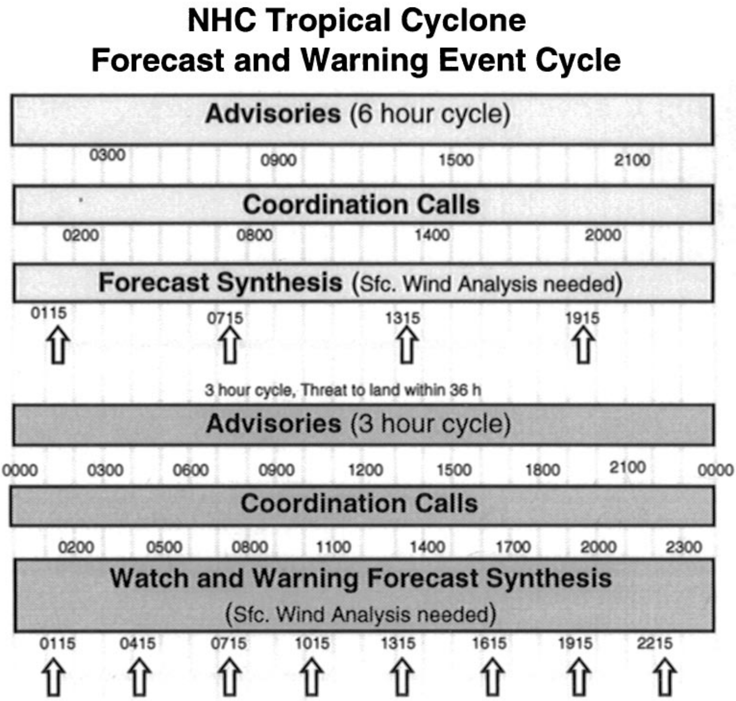

Fig. 5. Forecast and warning cycle of NOAA's National Hurricane Center.

project is supported, exposures will be documented as a function of upwind direction by using hand held photography and maps in accordance with the ASTM wind standard [10]. An example of upwind exposure at an automatic surface observing system (ASOS) at Cherry Point Marine Corps Air Station is shown in Fig. 7. At airport stations such as Fig. 7, the distance to tree lines is an important factor for determining roughness as a function of wind direction.

Based on all of the data and site information that were gathered, all of the Hurricane Fran observations were quality-controlled (Fig. 8a). Surface observations were given greater credibility than surface-adjusted aircraft observations, resulting in removal of many aircraft data during the QC process, primarily in locations where both types of data overlapped. Separate analyses were conducted (for marine and open-terrain exposures), and merged at the coastline to represent the appropriate exposure type and then combined with radar reflectivity measurements. The resulting surface wind analysis for Hurricane Fran at landfall (Fig. 8b) shows that peak surface winds ($>45\,\mathrm{m\,s^{-1}}$) were primarily over the ocean. In addition, a broad area of $>40\,\mathrm{m\,s^{-1}}$ winds were shown along the immediate coastline and winds $>34\,\mathrm{m\,s^{-1}}$ extended well inland to the north of Fran's center. Note that although the coverage of Fran's radar reflectivities are not impressive over the ocean at landfall, the peak reflectivities are $>50\,\mathrm{dBZ}$, which represents intense rainfall above $60\,\mathrm{mm\,h^{-1}}$.

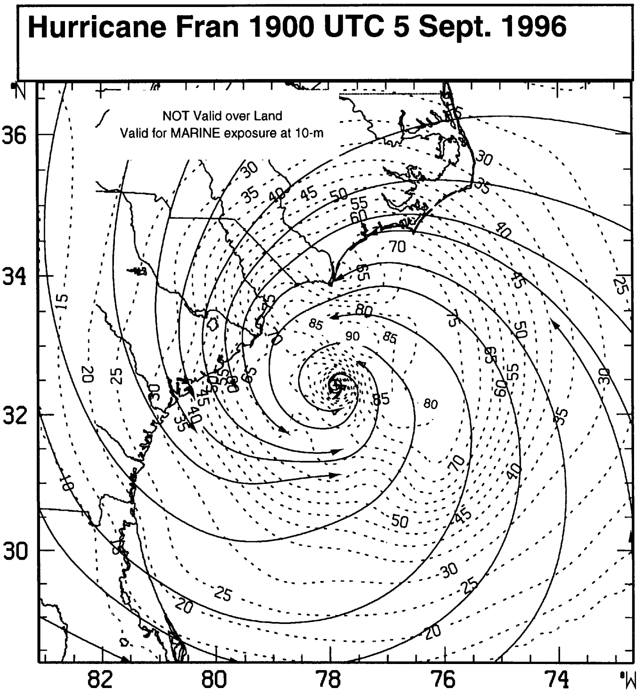

Fig. 6. Real-time analysis sent to NHC. Maximum sustained 1 min surface wind streamlines and Isotachs (kt) using: US Air Force Reserve recon. data adjusted to the surface from 3000 m during 1241–1820 UTC; buoys, drifters, ships, C-MAN from 1600–1800 UTC. 1900 UTC position extrapolated from 1751Z fix using 335° at 14 kts.

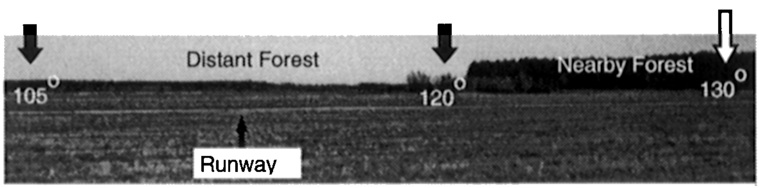

Fig. 7. Panoramic view looking outward from Cherry Point MCAS center field ASOS site. Numbers refer to compass headings.

4. Future plans and conclusions

Future improvements to WAnDA will be in the areas of database management, platform independence, distribution and load sharing. At present, WAnDA accesses data from a database of flat ASCII and binary files. Some drawbacks of such a database are the lack of extensibility and manageability. One of our objectives is to

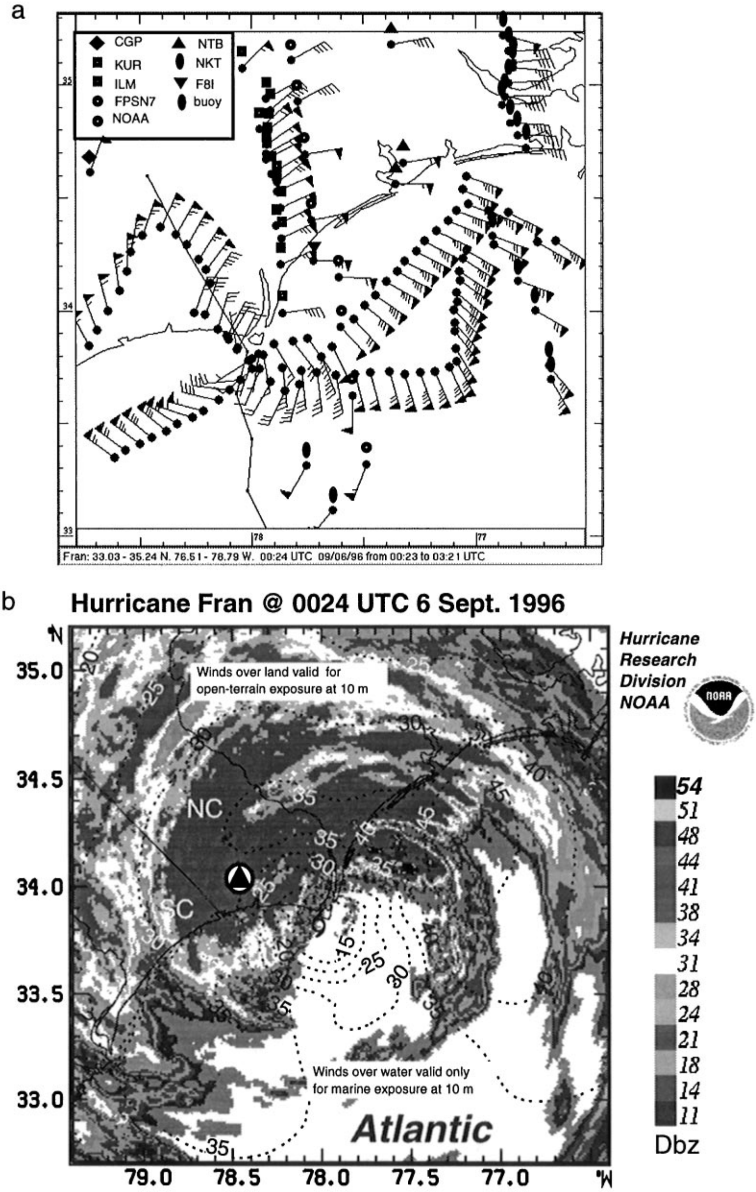

Fig. 8. (a) Post-storm distribution of quality-controlled data for Hurricane Fran's landfall. Observations are plotted relative to storm center at 0024 UTC, 6 September 1996. Wind barb orientation shows wind direction, end of bard represents speed with $5\,m\,s^{-1}$ for a full slash, $2.5\,m\,s^{-1}$ for half a slash, $25\,m\,s^{-1}$ for a triangle. (b) Post-storm analysis of Fran created by merging separate land and marine exposure wind analyses, and overlaying on National Weather Service WSR 88D radar reflectivity distribution from Wilmington, NC. Dashed contours represent maximum sustained (1 min).

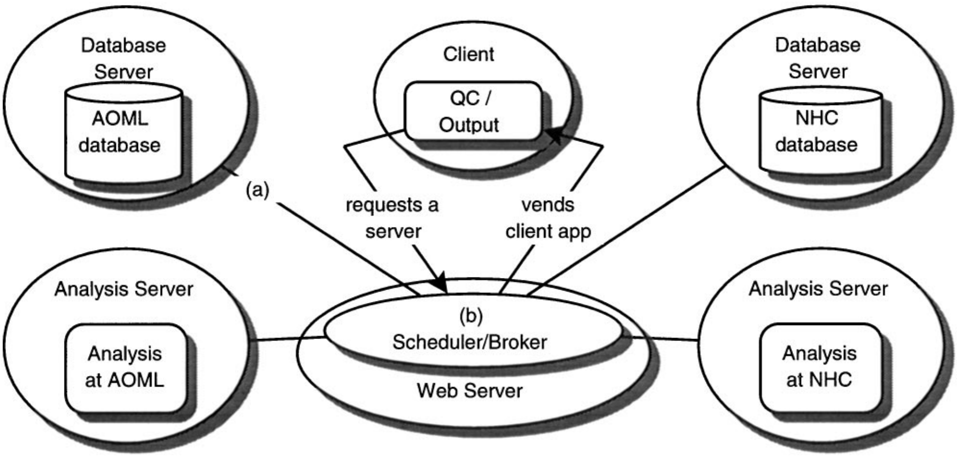

Fig. 9. Future WAnDA application structure. (a) All graph edges indicate possible lines of communication. Directed edges indicate specific actions along those lines. (b) The Scheduler/Broker handles all server requests, vends apps, and manages data flow and load balancing.

design and implement a database to store atmospheric observations, storm fixes, and analysis data for both operational and research purposes.

WAnDA's subsystems have been developed to run concurrently over two different computer platforms through the use of dynamically scripted UNIX and VMS ftp, rsh and rcp commands. Future system designs will incorporate a more robust client/server model and implementation (Fig. 9). In order to make WAnDA more accessible to scientists, its quality control (QC) and output subsystems will be redesigned to allow web client access and database connectivity. The goal is to be able to run the system over an intranet and later on the internet where distribution of applications, data, documents, and database connectivity and access can be realized via the World Wide Web. Redundant analysis servers and databases will also be needed in the likely event of a hurricane landfall in South Florida or during periods of heavy operational use. Selective server use and database mirroring in an object-oriented environment imply object distribution in order to stay within the OO paradigm. Tools such as Portable Distributed Objects (PDO) and Distributed Objects from Apple/NeXT Software[1] as well as various database management systems are currently under investigation.

Using a client side version of QC vended by a server will help balance the computational load of the proposed system between the browser and the web server. Furthermore, QC will act as an expert system by assigning each candidate observation a confidence factor to assist the user in decisions regarding the validity of an analysis set on the observation level. An improved web-based analysis and data

[1] Mention of a commercial product does not constitute an endorsement.

retrieval system would facilitate collaborative efforts with other agencies, emergency managers, utility and insurance-related groups, and university scientists and lead to improved products through interaction with the user community. A freely accessible archive of hurricane wind analyses will benefit segments of the scientific community working on improving the performance of space- and aircraft-based remote-sensing platforms by providing ground truth. Researchers studying wave and storm surge development and forecasting would be able to access gridded data sets to use for model initialization. Those working on improving hurricane wind field components of insurance- or infrastructure-related damage assessment models would have access to comparison data sets.

A web-based product menu would allow a user to generate a data file of a variety of swath type products in a format compatible with popular geographical information systems. Swath map products under consideration include maximum 3 s wind gust, duration of wind speed over a user-specified threshold, wind steadiness, wind load pressure, marine surface wind stress and wind stress curl. These products will allow creation of a localized database to support development of a damage assessment model tailored to a particular interest area. For example, a utility [11] could download wind swath quantities such as duration of winds in excess of hurricane force and maximum sustained wind speed for recent storms that may have affected their power grid. With several cases and geo-referenced information on losses to utility structures, the utility could begin to create their own model for damage assessment. Additional custom products could be designed to fit individual user's needs such as a time series product. For example, a user could choose a storm and time period of interest, enter a location of interest, and a plot of the time history of hurricane wind speeds and direction would be created, allowing the user to associate damage with the winds experienced.

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