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From D-Day to Drones, on Knowing What Observations are Necessary for Marine Operational Forecasting and on the Capacity Building Role of Academia in Research to Operations

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ABSTRACT

Deciding when the United States (U.S.) and its Allies would launch the World War II (WWII) D-Day invasion of the Normandy beach of France, in 1944, was an operational nightmare. Observations were scant and forecasting hourly to daily atmospheric storm conditions, visibility, and oceanic currents and waves in the English Channel were all highly problematic, at best. Finally, on June 6th, the decision was made that there could be a break in the atmospheric and oceanic weather allowing for the storming of the Normandy beach in France and the invasion of Europe. At that time, observational atmospheric and oceanic data were not comprehensively available and decisions had to be made quite literally, on the fly. Following the end of WWII in June 1945, the U.S. Congress decided that a federal agency focused on gathering more and better atmospheric and oceanic state variable data was needed to undergird more advanced operational forecasting over periods of hours to days to weeks. Thus in 1946, the U.S. Office of Naval Research (ONR) was created to provide research monies to universities across the U.S. to train the next generation of scientific experts which would lead to greatly improved atmospheric and oceanic operational forecasting or so it was assumed. The two communities of environmental sciences, the atmospheric or dry contingent, and the ocean sciences or wet contingent went separate ways with their newly gained resources from ONR and the subsequent history of "weather" forecasting in the U.S. has sputtered along but has never been merged either observationally nor from a numerical modeling perspective nor even culturally amongst the atmospheric and oceanic communities. This manuscript describes the history of operational weather forecasting in the U.S. The pitfalls, several failed attempts by academia to address the challenges, the role that universities can play in serving the research needed to improve NWS forecasting and several new federal agency and university programs that are attempting to address national needs in operational forecasting.

Key Words: observations, operational forecasting, atmospheric forecasting, marine forecasting, weather, climate

INTRODUCTION

The history of atmospheric and oceanic operational forecasting have different histories and separate tracts in the U.S. Atmospheric sciences forecasting of the "weather" began ostensibly on February 2, 1870, when the U.S. Congress passed a resolution requiring the Secretary of War "to provide for taking meteorological observations at the military stations in the interior of the continent and at other points in the States and Territories, and for giving notice on the northern Great Lakes and on the seacoast by magnetic telegraph and marine signals, of the approach and force of storms." The Resolution was signed into law on February 9, 1870 by President Ulysses S. Grant, and the precursor to the National Weather Bureau (NWB) and National Weather Service (NWS) was born. The new agency, called the Division of Telegrams and Reports for the Benefit of Commerce, was formed under the U.S. Army

Signal Service. The new weather agency was placed under the War Department because "military discipline would probably secure the greatest promptness, regularity, and accuracy in the required observations." Because of the long name, the agency frequently referred to it as the national weather service or general weather service of the U.S. The new weather agency operated under the Signal Service from 1870 to 1891. During that time, the main office was located in Washington, D.C., with field offices concentrated mainly east of the Rockies. Most forecasts originated in the main office in Washington with observations provided by field offices. During the Signal Service years, little meteorological science was used to make weather forecasts. Instead, weather which occurred at one location was assumed to move into the next area downstream. The weather forecasts were simple and general in content, usually containing basic weather parameters such as cloud and precipitation. The Division of Telegrams and Reports for the Benefit of Commerce remained under the Signal Service until 1891.

On October 1, 1890, Congress voted to transfer it to the Department of Agriculture and renamed the Weather Bureau, and at that time, organized civilian weather services within the Federal Government began in the U.S. The Weather Bureau was part of the Department of Agriculture for 50 years from 1891 to 1940. During that time, considerable improvements were made in Weather Bureau operations, and the science of meteorology made significant advances. Weather forecasters in the Signal Service and early NWB years primarily used information from surface weather observations. The early meteorologists were aware that conditions in the upper-atmosphere controlled surface weather conditions, but technology had not advanced to the point of taking upper atmospheric observations. In 1900, the NWB began to experiment with kites to measure temperature, relative humidity, and winds in the upper atmosphere. Kite observations were taken intermittently from about 1900 to about 1920 with a kite network of stations established during the 1920s and early 1930s. These pioneers were the first to observe classical meteorological features which significantly impacted weather over the United States. By the early 1930s, kites were becoming a hazard to airplanes in flight, causing kite observations to give way to airplane observations. In 1931, the NWB began to replace kite stations with airplane stations. The use of the airplane as an upper-air observational tool continued to expand during the 1930s. Airplanes were an expensive and dangerous way to obtain upper-air data. Also, it frequently was impossible to use airplanes during bad weather; the time when observations were most important. The disadvantages of the airplane as a sounding platform, coupled with the advent of sounding balloons carrying meteorological instruments and radio transmitters (radiosondes), resulted in airplane observations being discontinued prior to WWII. The development of the radiosonde was a benchmark to operational meteorology. With the relatively inexpensive instrument, the upper atmosphere could be sampled routinely and simultaneously in both bad and good weather. The radiosonde was one catalyst which increased meteorologists' understanding of the weather. Following the implementation of the radiosonde, the science of weather forecasting began to improve substantially and steadily. One of the more important advances for the NWB while in the Department of Agriculture was the advent of the teletype system. The forerunner of the teletype, the telegraph, served the early needs of the agency, but it was readily apparent that this system was labor intensive and not reliable. The system contained many vulnerable areas, any of which could result in an important warning not being received or a critical observation not transmitted. The teletype was introduced in the NWB in 1928 and its use spread rapidly. Within two years, teletype circuits covered 8,000 miles, mainly in the eastern part of the country, and by the mid-1930s, teletype circuits covered over 32,000 miles. While under the Department of Agriculture, aviation weather services of the NWB expanded rapidly. Initiation of air mail flights and the increase of aviation activity following World War I placed a large demand on the NWB for forecasts of flying weather. In 1919, daily flying weather forecasts were started primarily for the U.S. Postal Service and military aviation, but the most significant advances occurred with the passage of the Air Commerce Act of 1926 which made the NWB responsible for weather services to civilian aviation. The Air Commerce Act increased aviation weather services, and more importantly, the law provided funds to establish a network of stations across the U.S. to take surface and upper-air weather observations. As the NWB became more associated with the aviation community, it became apparent that the agency belonged in the Department of Commerce (DOC). On June 30, 1940, U.S. President Franklin Delano Roosevelt transferred the NWB to the Department of Commerce where it remains today as the NWS. The early association of the NWB with the DOC was dominated by WWII. Although most NWB meteorologists were deferred from military duty, many elected to serve their country. As the supply of males was short, American women stepped in to perform the jobs at the NWB.

In contrast to the bright morning about to dawn over Portsmouth, England, on June 4, 1944, gloom settled over the Allied commanders gathered inside Southwick House at 4:15 a.m. Years of preparation had been invested in the invasion of Normandy, but now, just hours before the launch of D-Day operations, came the voice of Group Captain James Stagg urging a last-minute delay. As Operation Overlord’s chief meteorological officer, Stagg was hardly a battlefield commander, but the ultimate fate of D-Day now rested in his decision-making. The disappointed commanders knew that the list of potential invasion dates were only a precious few because of the need for a full moon to illuminate obstacles and landing places for gliders and for a low tide at dawn to expose the elaborate underwater defenses installed by the Germans. June 5, chosen by Allied Supreme Commander Dwight Eisenhower to be D-Day, was the first date in a narrow three-day window with the necessary astronomical conditions. The massive Normandy landings, however, also required optimal weather conditions. High winds and rough seas could capsize landing craft and sabotage the amphibious assault; wet weather could bog down the army and thick cloud cover could obscure the necessary air support. The critical, but unenviable task of predicting the English Channel’s notoriously fickle weather fell to a team of forecasters from the Royal Navy, British Meteorological Office and U.S. Strategic and Tactical Air Force, and as D-Day approached, storm clouds brewed inside the meteorological office.

Weather charts on the wall map in the map room at Southwick House, Southwick Park, Portsmouth, which was the nerve center of planning for the Normandy landings and the headquarters of General Eisenhower during the D-Day operation. Observations from Newfoundland taken on May 29 reported changing conditions that might arrive by the proposed invasion date. Based on their knowledge of English Channel weather and observations, the British forecasters predicted the stormy weather would indeed arrive on June 5. The American meteorologists, relying on a different forecasting method based on historic weather maps, instead believed that a wedge of high pressure would deflect the advancing storm front and provide clear, sunny skies over the English Channel. In the early hours of 04 June 4, Stagg believed foul weather was only hours away. He sided with his fellow British colleagues and recommended a postponement. Knowing that the weather held the potential to be an even fiercer foe than the Nazis, a reluctant Eisenhower agreed in the early hours of 04 June to delay D-Day by 24 hours.

On the other side of the English Channel, German forecasters also predicted the stormy conditions that indeed rolled in as Stagg and his fellow Brits had feared. The Luftwaffe’s chief meteorologist, however, went further in reporting that rough seas and gale-force winds were unlikely to weaken until mid-June. Armed with that forecast, Nazi commanders thought it impossible that an Allied invasion was imminent, and many left their coastal defenses to participate in nearby war games. German Field Marshal Erwin Rommel returned home to personally present a pair of Parisian shoes to his wife as a birthday present. German Luftwaffe meteorologists, however, relied on less sophisticated data and models than their Allied counterparts, says John Ross (2014), author of *The Forecast for D-Day: the Weatherman behind Ike's Greatest Gamble*. "The Allies had a much more robust network of weather stations in Canada, Greenland and Iceland; weather ships and weather flights over the North Atlantic and observations by secret agreement from weather stations in the neutral Republic of Ireland." Those weather stations, in particular one at a post office at Blacksod Lighthouse Point in the far west of Ireland, proved crucial in detecting the arrival of a lull in the storms that Stagg and his colleagues believed would allow for an invasion on June 6. As rain and high winds lashed Portsmouth on the night of June 4, Stagg informed Eisenhower of the forecast for a temporary break. With the next available date for an invasion nearly two weeks away, the Allies risked losing the element of surprise if they waited. In spite of the pelting rain and howling winds outside, Eisenhower placed his faith in his forecasters and gave the go-ahead for D-Day. The weather during the initial hours of D-Day was still not ideal. Thick clouds resulted in Allied bombs and paratroopers landing miles off target. Rough seas caused landing craft to capsize and mortar shells to land off the mark. By noon, however, the weather had cleared and Stagg's forecast had been validated. (Figures 1, panels left and right). The Germans had been caught by surprise, and the tide of World War II began to turn. Weeks later, Stagg sent Eisenhower a memo noting that had D-Day been pushed to later in June, the Allies would have encountered the worst weather in the English Channel in two decades. "I thank the Gods of War we went when we did," Eisenhower (aka "Ike") scribbled on the report. He could also have been thankful for Stagg overruling the advice of the American meteorologists who wanted to go on June 5 as planned, which Ross says would have been a disaster. "The weather over Normandy contained too much cloud cover for Ike's greatest strategic asset, the Allied air forces, to effectively protect the landings from German armor, artillery and infantry reserves. Winds were too strong for the deployment of paratroopers to secure bridges and crossroads inland from the beaches thus preventing German reinforcement of coastal positions. Waves were too high for landing craft to put soldiers and supplies ashore. The key element of surprise, location and time, would have been lost, and the conquest of Western Europe could well have taken much longer with many more lives lost by the U.S. and Allies.

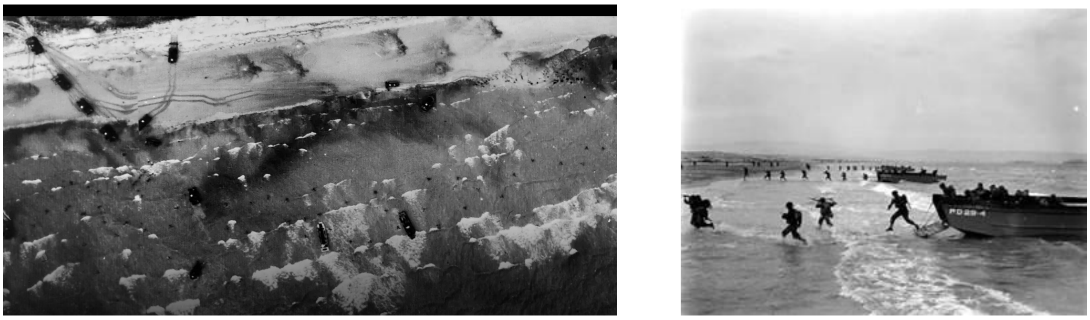

Figure 1. WWII –Day Normandy Landings. Left panel, U.S. Higgins Boats dropping off U.S. Troops; Right panel, U.S. Troops disembarking the Higgins landing craft.

In the 1930's, well prior to D-Day, research and development (R&D) of crucial war technology was being conducted in the U.S. in Tuxedo Park New York, a palatial estate on the banks of the Hudson River owned by Alfred Lee Loomis, an American attorney, investment banker, philanthropist, scientist, physicist, inventor of the LORAN Long Range Navigation System and a lifelong patron of scientific R&D. Loomis' role in the development of microwave radar and the atomic bomb contributed to the Allied victory in World War II. He invented the Aberdeen Chronograph for measuring muzzle velocities, contributed critically, to the development of a ground-controlled approach technology for aircraft, and participated in preliminary meetings of the Manhattan Project. As political and military trouble was brewing in Europe, Loomis saw the need for new advanced R&D in the U.S. and invited scientists from Europe to live and conduct their research at Tuxedo Park, with living, travel and research expenses provided. Basically Loomis, out of pocket, underwrote much of the costs of R&D for WWII, which changed the course of WWII. The story is documented in *Tuxedo Park, A Wall Street Tycoon and the Secret Palace of Science That Changed the Course of World War II*, by Jennet Conant (2013). Moreover, following the collaborative development of microwave radar, Loomis contacted his first cousin (on his Mother's side) Henry Stimson, the U.S. Secretary of War, and apprised him of this breakthrough technology. Stimson contacted President Franklin Delano Roosevelt, and their meeting resulted in the application of the technology that arguably won WWII. The U.S. and its Allies knew where all of the German planes and ships were and actually had to hide that fact because they had to hide that breakthrough from the Germans. Sir Winston Churchill, Prime Minister of England, was quite pleased with the new technology. But, once again, this was a technological advance made via private, not federal R&D. Prior to WWII, the ocean sciences community's approach to the creation of coastal ocean observing systems evolved from a relatively primitive approach of throwing surface drifters into the coastal ocean along with shipboard observations in response to the expressed U.S. Congress needs for more information about the oceans.

Immediately following the end of WWII, the U.S. federal government realized that much of the R&D responsible for the victory of the U.S. and its Allies over the Nazis and Fascists, had been privately subsidized, mainly at Tuxedo Park NY. The key question raised was: Why were the atmospheric and oceanic weather forecasts so problematic. The solution was to improve the capability at a massive scale. So, as a practical imperative, this situation called for the creation of a federally funded, academia based national research program in both the ocean and atmospheric sciences. The challenges of not knowing when to cross the English Channel because of a lack of ability to properly forecast the atmospheric and oceanic "weather" nearly compromised the Allied invasion of Normandy. Clearly that experience showed that the U.S. needed a far more ambitious national atmospheric and oceanic research enterprise with an associated strategy to transfer the results of the research to new operational forecast tools. This led to the immediate creation of the U.S. Navy's Office of Naval Research (ONR), in 1946. Following the success of the ONR enterprise, the U.S. National Science Foundation (NSF) was created using the ONR template, but including all of the sciences, mathematics and engineering in 1949. NSF's funding was intended to begin a new era of scientific and technological advances to drive the Nation's economy. ONR's funding was intended to establish the oceanic and atmospheric sciences necessary to undergird better oceanic and atmospheric weather forecasting, as shared by Dr. Earle G. Droessler, the first ONR Program Manager (p.c.). However things did not turn out as originally conceived and planned. Here is the story of separate tracks taken between the wet (oceanic) and dry (atmospheric) academic communities. At ground zero in 1946, it was a cultural divide that has endured for eight decades.

Across the community of academic atmospheric scientists, the challenge in the mid-1940s was viewed as one that merged education at the PhD and undergraduate levels. The training of new PhDs was fast tracked in order to create a national cadre of faculty to teach undergraduates to become line weather forecasters with the U.S. Weather Bureau. This emergence of a national network of principally undergraduate programs was then followed, in 1959 by the creation of a national consortium of universities, the University Corporation for Atmospheric Research (UCAR) and a National Science Foundation (NSF) national laboratory, the National Center for Atmospheric Research (NCAR) was established and funded following the model https://nationallabs.org/our-labs/, established by the U.S. Department of Energy's National Laboratories. UCAR and NCAR were created and funded by NSF's Program Manager, Dr. E.G. Droessler, who, in 1949, had left his position at ONR and who then established a position in-kind at the newly formed NSF. UCAR and NCAR were the visions of

Dr. Thomas Malone, a Professor at the Massachusetts Institute of Technology who brought his idea to Droessler. Both UCAR and NCAR and the wide-ranging university community have prospered with this arrangement in which large research facilities are centered at the UCAR/NCAR headquarters in Boulder, CO. The UCAR and NCAR pair is an example of a good idea being put forward for a common cause and is deemed to be a highly successful model originally to serve the national collective needs of the atmospheric sciences community and which has evolved over the decades to now serve the North American (the U.S. and Canada) academic research and education earth systems community of scientists broadly defined.[1]

Alternatively, the ocean sciences community responded to the ONR and NSF opportunities with the creation of coastal laboratories at major Pacific and Atlantic (including the Gulf of Mexico) coastal and Great Lakes universities, and programs that specialized in graduate education and field research. These major university ocean and lake sciences programs acquired sea going vessels and obtained funding from ONR in 1946 and then from NSF in 1949, to support institutional infrastructure. These institutions competed for block funding, sent faculty to serve as ONR and NSF program managers, and interacted collaboratively when conducting complementary experiments on NSF University Oceanographic Laboratory System (UNOLS) cruises employing the new fleet of ocean going vessels. To date, the UNOLS model has been very successful. Albeit, to the present, the ocean sciences community is not fully integrated having gone from the Joint Oceanographic Institutions (JOI), the Consortium for Oceanographic Research and Education (CORE) along with the National Association of Marine Laboratories (NAML), to the Council on Ocean Leadership to the present day Center for Ocean Leadership (the COL), which is now co-located as a core office at UCAR in Boulder CO.

Students graduating from the atmospheric sciences programs in the 1950s and 1960s were hired by the NWB, while those from the ocean sciences institutions were hired by other universities. Thus the die was cast, the atmospheric sciences academic programs were traditional, with a strong base of undergraduates and associated graduate programs; many tied to NCAR via UCAR. Faculty had conventional appointments since there was a strong undergraduate teaching presence and graduate students could be funded on both research and teaching assistantships. Alternatively, the oceanic sciences academic community, save for several outlier institutions, was principally focused on grant and contract funded research with each institution having to build out its own infrastructure on federal funding and overhead receipts derived from indirect costs charged to the federal agencies by the universities. Faculty appointments were to a large degree based on soft money, not a stable sustainable situation and graduate students were supported as research assistants.

During the war years, meteorological services by the NWB increased significantly. Following the creation of ONR and its funding of atmospheric sciences across the Nation, the main contribution to NWB operations was in the area of radar meteorology and computer models of the atmosphere at the universities. During the late 1940s, the U.S. military gave the NWB 25 surplus radars which subsequently were renovated to detect weather echoes. Information gained from the operation of these radars eventually led to the formation of a network of weather surveillance radars still in use today. With the development of computer technology during the 1950s the way was paved for the formulation of complex mathematical weather models to aid meteorologists in forecasting. The first operational use of these computer models during the 1950s resulted in a significant increase in forecast accuracy. At these universities there were weather stations attended to by faculty and staff.

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[1] https://www.bing.com/search?pc=U523&q=the+university+corporation+for+atmospppheric+research&form=U523DF

With the creation of NOAA in 1971 and the emergence of the NOAA NWS, and given the national network of NWS Weather Forecast Offices (WFOs), there were expanded opportunities for the nation's atmospheric sciences undergraduate majors to be employed as line-forecasters at the NWS WFOs. Thus the tradition and challenge of 24/7/365 operational forecasting became foundational to the culture of atmospheric scientists. This was not the case on the oceanic sciences side of the house. The ocean sciences community took a different tact. Here, there were few undergraduate majors and those graduates either went off to graduate school or found employment in other fields or in the U.S. Coast Guard. So, the tradition established in the ocean sciences was one of research in the pursuit of new knowledge and more research. Oceanic data was collected and generally stored in faculty cabinets. That was and the status quo, with no realization of real-time forecasting, save for NAVOCEANO, which is focused on the needs of the operational U.S. Navy. This history and tradition still exists within the ocean sciences community as it takes on a new challenge of real-time forecasting, in literally uncharted waters. This lack of appreciation of real-time forecasting has greatly and detrimentally impacted the build-out of the Nation's observing networks.

In 2000, the newly formed National Oceanic & Atmospheric Administration (NOAA) Science Advisory Board (SAB) recommended to NOAA that it commission a National Academy of Sciences National Research Council study of coastal and ocean observing networks. The question was: "is the NOAA National Ocean Service (NOS) and National Data Buoy Center (NDBC) network adequate to meet the Nation's needs for operational oceanic weather forecasting". The NOAA SAB had pointed out that the national NWS in-situ land based atmospheric observing network was 100 times more spatially extensive than the NOAA oceanic based network. The outcome of the study, the NRC report (Bosart & Pietrafesa, 2001) called for a nationwide expansion of coastal observing networks and U.S. This finding did not go unnoticed. Congressional earmarks ensued. NOAA's budget became filled with academic funding appropriations targeted for regional observing systems, of various sorts, attached to a variety of universities, with no overall plan or goal involved. The funding added up to several tens of millions of dollars without foci, other than "to collect data". This was not what the NOAA SAB nor the NAS NRC Report had recommended. However, another unfortunate event enfolded on Capitol Hill at that time. To wit, congressional earmarks were, on paper, shut down by Congress. They were deemed to be unnecessary largesse and wasteful spending. That said, to save face, Congress decided to allow "legacy earmarks" to justify their prior earmarked expenditures and, to continue them "in-kind".

Therefore, following the shutdown of earmarks in the early 2000's, Capitol Hill legislated the Integrated Ocean Observing System (IOOS) network as an Earmark Legacy Network (ELN), overseen by Regional Coastal Ocean Observing System associations (R-COOSs). IOOS was rationalized by the NOAA SAB based on the need for the establishment of a national backbone to greatly improve atmospheric, oceanic and coastal "weather" forecasting, broadly defined, for ecosystem management and to document climate variability and change in coastal zones. However the ELN overseer universities had no skill-sets in forecasting, only in collecting data, and NOAA's NOS did not follow the SAB intentions. Further, the NOAA SAB recommended that all Fishing Pier Owners be approached for the establishment of secure observing systems at the many Piers around the coastline of the U.S. For example, between Maryland and Florida there are about 70 fishing piers. But NOAA had no line item for this type of expenditure and no overall champion on Capitol Hill to put this into a bill, nor were there local demands expressed by universities for these costs. So these national structural treasures remain observational voids. One university funded by NOAA did establish a regional network of 5 fishing pier observing systems. But that program ended when the funding expired, much to the chagrin of the pier owners as the public pier visitors thoroughly enjoyed observing the live data feeds coming up the hard wired sensors into monitors in the Fishing Pier Houses. One could argue that both the ARGO and IOOS approaches were based on sound rationale but the IOOS approach was not well organized with substantive value, given the way it was orchestrated within NOAA's NOS. IOOS has been a failure in operational oceanic forecasting. The existing IOOS failure is both historical and cultural. The rationale for why and how to build the ensuing Coastal Ocean Observing Systems (COOSs) was not well based. Words such as "improving marine services", "predicting hurricanes" and so on were and still are basically, statements without value or substance. What was and is still needed?

A better answer to the question of what would justify NOAA investments in IOOS with a comprehensive rationale could and should be: 1) to provide better operational forecasts of atmospheric and ocean "weather" (used broadly to mean high frequency events in both air and water); to document and predict coastal impacts of weather events to environmental systems and human systems; 2) to document the impacts of human alterations on coastal systems; 3) for under-girding the data and information bases on which to conduct ecosystem management decision making; 4) to document climate variability on regional to sub-regional scales; and 5) to help coastal and inland communities impacted by hazardous coastal weather to build resilience. But this will require an ocean sciences culture trained in the mechanics of diagnostic retrospectives, of conducting observation simulation experiments (OSE's), of doing prognostic driven modeling experiments and of the process of operational "forecasting". To lowest order this rationale must also include the challenge of building, deploying and sustaining coastal observing systems which must operate reliably and routinely report data in near real time. These are cultural and operational challenges to the ocean sciences community, which existed in 2000 and still exist today.

As discussed above, with ONR and then NSF funds, the ocean sciences community spent its R&D funds on purchasing a fleet of ocean going vessels, which were housed at major universities around the Atlantic, Pacific and Gulf coastlines, of the U.S., hiring new ocean sciences faculty to teach existing knowledge about the oceans and on graduate student support to conduct shipboard studies of the ocean basins and create new knowledge of the oceans. There was no focus on operational forecasting as the ocean was perceived as being a slow moving fluid unlike the rapidly changing atmosphere. Meanwhile coastal oceanic studies were few, with federal agencies such as the U.S. Energy Research & Development Agency (ERDA) which morphed into the Department of Energy (DOE), leading coastal studies mainly to better understand the potential dangers which near coastal nuclear power plant accidents posed to residents living around the U.S. coastlines.

Contemporaneously, the Argo Program was developed in 1999, (named after the Greek mythical ship Argo, captained by the mythical Greek hero, Jason), initially funded by several U.S. federal agencies and overseen by NOAA.[2] Today the program supports a global array of ~ 4,000 robotic profiling floats that measure the temperature and salinity of the upper 2,000 meters (1.2 miles) of the ocean. The Argo Program, which has far surpassed what ships can accomplish, has an international reach with participation from close to 30 countries. This partnership allows, for the first time, constant monitoring of the temperature, salinity, and currents of the upper ocean. Argo floats are now being tested to dive down to a depth of 6,000 meters (3.7 miles) and have additional sensors on them to collect information about the biology and the chemistry (oxygen, pH, nitrate, suspended particles, and down-welling irradiance) of the global ocean. Argo floats work on a 10-day cycle. After 10 days, the floats rise to the ocean surface and send their data to satellites. These data are available within hours after collection and used in international research.

The next section presents a description of some cultural pitfalls that may be impeding the direction, progress and future success of these IOOS special allocation programs, particularly

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[2] https://globalocean.noaa.gov/Research/Argo-Program/

as they relate to oceanic operational forecasting. If there are real partnering opportunities and advantages to these alliances, they must be acknowledged by the target federal agencies, specifically NOAA, if they are to succeed and prosper. The alternative may be a missed window of opportunity in building a national monitoring network that has value to NOAA and to the citizenry of the U.S. at national to sub-regional scales. Albeit, the discussion points to a subset of regional programs with attention to the negatives, pitfalls, challenges, opportunities and advantages of the loosely structured federal agency and university community partnership. An example of one such program is presented by focusing on a coastal network in the region of the Carolinas originally designed for oceanic operational forecasting; but which folded as it was not able to continue, as it was not based on a legacy earmark.

BACKGROUND AND PRESENT SETTING

NOAA is the lead domestic agency charged with providing coastal environmental data and information to the Nation In Fiscal Year (FY) 2006, \$138M of earmarked monies were spent in support of the national patchwork quilt of Coastal Ocean Observing Systems (COOSs). In FY07 U.S. House of Representatives appropriations language, NOAA was encouraged to formally request monies from Congress in support of building out ocean and coastal observing systems, specifically for forecasting. At the same time and perhaps as a step forward, the university community could have considered not being concerned solely with their own self-interests and introspective and becoming more focused on service-research. But it did not. Contemporaneously, NOAA, which does not have the broad in-house technological expertise that the national network of universities possess, might have looked to the value of allowing universities to test new technologies, to fail or succeed, and to adopt and make operational what worked better than was already being employed. Universities are familiar with trying and failing, but also with trying again until success is achieved. That is part of the academic process.

NWS is an organization that epitomizes the characteristics for needed, demanded and required federal organizations. It is a solid example of what an agency, federal or state, could and should be in support of, that is in serving the needs of the citizenry of the Nation. Another example of a similar federal agency is the U.S. Postal Service (USPS). Both have to deliver routinely on schedule and thus, operationally. Albeit, the USPS has never had a successful business model and the NWS had never seriously considered the justification, rationale or strategy for a greater presence in the ocean or coastal areas of U.S. waters. By way of comparison, there are presently the order of 20,000 land based atmospheric monitoring sites across the U.S, but only 140 NDBC marine buoys and Coastal Marine Automated Network (CMAN) stations in coastal waters including the Atlantic, Pacific, Gulf and Great Lakes coasts; nominally a 150/1 ratio. The issues are several fold. It is generally assumed that knowledge of and forecasts for coastal weather, i.e., high frequency events, is very important in both the coastal atmosphere and coastal waters, but not on land. Secondly it's generally assumed that weather over land was spawned on land. Thirdly, what's the big deal anyway? The reasons are several-fold: 1) about 45% of the U.S. population now lives in coastal counties; 2) there have been many weather related events which have had enormous economic impacts in these coastal zones; and (3), given (2), the cost of weather disasters to the U.S. economy by 2030 could reach approximately \$3 Trillon/year.[3] The interactive coupling of coastal and inland weather processes are intrinsically interactively coupled, as the Pacific, Atlantic and Gulf of Mexico water bodies all play important roles in the overall synoptic scale to meso-scale regional to local weather.

Would more and better information coming routinely from these coastal regions improve NOAA NWS National Centers for Environmental Prediction (NCEP) forecasting capabilities?

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[3] https://www.bing.com/search?pc=U523&q=noaa+billion+dollar+weather+disasters&form=U523DF

In 2004, the NOAA NWS National Centers for Environmental Prediction (NCEP) requested and the NOAA SAB commissioned an external study of the status and value of NCEP ocean modeling and all that it entails. In its comprehensive evaluation and as documented in its report (Pietrafesa et al., 2004) the case for a greatly expanded ocean and coastal observing array was a resounding “yes”. The data are needed for more comprehensive in-situ spatial and temporal coverage, for providing actual, real coastal environmental state parameter conditions, for validating satellite sensors, none of which directly measure the parameters of interest, for initializing atmospheric and oceanic numerical models, for data ingestion and assimilation into atmospheric and oceanic numerical models, for driving and validating weather forecast numerical model output, for conducting hind-casts and retrospective analyses, for now-casting, and for improved forecasting. Moreover, if interactively coupled air-sea models are to be run routinely on the NCEP computational platforms, data must be collected on both sides of the air-water interface at the same place and time. Historical perspective is of value here, because a cultural separation has existed for at least six decades, if not longer, and it has impeded progress. Herein NWS WFO forecaster and university staff and students could benefit from close interaction with each other. While WFO staff are challenged by operational challenges and do not have the time or resources to address these issues, university faculty and students can do just that. This drives O2R and thus R2O. This has happened, where the situation was present for a close location of a WFO near or on a university campus (National Research Council, 2012).

Several NWS WFOs collocated on or near a university started with the earliest being at Pennsylvania State College (PSU) PA, in 1993, followed by the WFO in Fairbanks AK in 1998 with the University of Alaska-Fairbanks, the National Hurricane Center (NHC) Florida near Florida International University, the WFO in Honolulu HA near the University of Hawaii - Honolulu, the WFO Raleigh collocated on the North Carolina State University Centennial campus, and WFO Tucson, at on the University of Arizona-Tucson campus. Three offices are located adjacent or close to a university campus from a few blocks to a 25-minute walk (NWS Albany, WFO Rapid City, and WFO Denver/Boulder. Five WFO offices are located in the same city as a university with atmospheric sciences programs, including WFO’s in Reno NV, San Francisco CA, Seattle WA, in research parks or annexes one to three miles away. The results of colocation with regard to regular interaction between the WFO’s and university scientists appear to be somewhat varied but, overall, the responses indicate successful sustained, regular, and beneficial bidirectional interactions at 9 of the 12 NWS offices. The extent of these does not appear to be correlated with how close the NWS offices are to the campuses, although true colocation seems to have provided clear benefits. Three of the five “On Campus Offices" (WFO Honolulu, WFO Raleigh, and WFO Tucson) report very extensive bidirectional interactions, while the other two (WFO Fairbanks and NHC Florida) report no “regular” interactions, with interactions being more on an as-needed basis. Very strong, mutually beneficial interactions appear to have developed at WFO Raleigh (North Carolina State University). These include NWS-hosted internship courses offered for credit and with competitive selection of students (the course was highlighted in the Bulletin of the American Meteorological Society in October 2005), monthly integration of students into NWS activities and projects, participation of NWS staff in the NCSU student chapter of AMS, collaborative projects funded through NOAA programs and research meetings/workshops many times a year to discuss successes and challenges of funded research, meteorological challenges for focus in future research proposals, data gathering efforts, and other similar activities.. Beneficial interactions at WFO Tucson (University of Arizona) include research collaboration, communicating weather, water and climate issues to the community, and providing an academic institution easy access to an operationally oriented organization. Within any one year period, WFO Tucson is usually involved in two research projects with faculty and graduate students, jointly conducts press conferences on science issues and participates in three to five meetings associated with integrating advances in science into an operational setting. Similar benefits appear to be realized at WFO Honolulu (University of Hawaii). Similarly, the three "near campus offices" report fairly successful interactions. WFO Denver/Boulder reports multiple daily interactions ranging from weather briefings to side-by-side work in the forecast operations area, regular interactions such as project and science presentations and participation in seminars and workshops at NCAR and UCAR. Several NOAA Cooperative Institutes (CIs), such as the Research in Environmental Sciences (CIRES at the University of Colorado in Boulder CO) and Research Applications (CIRA at Colorado State University in Fort Collins CO) provide strong educational experiences for NWS staff. NWS Albany, NY, is engaged in active NOAA grants, hosts 16 University of Albany interns each year, employs two to three students per year, and benefits from University conference facilities. The WFO Rapid City SD reports participation in seminars, substitute teaching, collaborative research meetings, and the Scientific & Operations Officer (SOO) serving on thesis and dissertation committees. WFO Seattle benefitted from and contributed to the collaboration with University of Washington atmospheric scientists on the science of weather forecasting. This led to improvements in the understanding of the local weather of the Pacific Northwest. University of Washington atmospheric scientists took O2R from the WFO staff and via R2O improved weather observations locally and the Seattle WFO benefited from this.

At NCSU, several graduate students created operational forecast tools for the formation of Mid-Latitude Cyclones during the NSF-sponsored Genesis of Atlantic Lows Experiment (GALE), coupled with the DOE sponsored Ocean Margins Program OMP), a NOAA also sponsored Southeast Consortium for Severe Storms, a five university consortium, headquartered at NCSU. NCSU scientists routinely worked with the WFO forecasters to get evacuation orders issued by former NC Governors, J. Hunt and J. Martin prior to incoming hurricanes and Mid-Latitude Cyclones ahead of massive flood events on the NC Outer Banks; with 1000's of lives saved. Subsequently, in 1997, NOAA and the NWS joint Headquarters awarded the Raleigh WFO a NOAA Unit Citation Award and named the WFO Office and five NCSU faculty for exceptional O2R and R2O advances. Again, the Raleigh WFO reports very extensive benefits from the close partnership including sharing of data and building of critical datasets used by the North Carolina State Climate office (also collocated). NCSU was able to locate a NWS WSD Radar on a University Extension Service Farm at no-cost to NOAA and to get the State of NC to contribute 42 additional NWS instrumented sites across the state of NC to supplement the 27 NWS sites. In an interesting arrangement, rent monies paid by WFO Honolulu to the University of Hawaii are used to support a full time Graduate Research Assistant, two summer teaching assistants, six undergraduate student assistants, and some operational costs.

While some challenges with respect to colocation do exist, one common theme is the lack of sufficient funding to support the activities that benefit from colocation. In almost every case, more benefits would likely accrue if more financial support could be devoted to university collaborative activities. In a different vein, there can be difficulties related to the nature of the facilities. For example, the experience of Honolulu WFO indicates that colocation can raise difficulties with regards to access to staff and visitor parking. This can cause security issues for shift workers. Meanwhile WFO Raleigh points out that in a facility directly-owned by NWS, the office is more able to solve facilities-related problems on its own or through providers of its choosing. In a facility leased from a campus, facilities issues must usually be directed to campus facilities personnel with more complex procedures to be followed such as work orders, facilities modification form completion and approvals) to get work accomplished. Sometimes, apparently very simple work needs to be completed by University personnel at a cost, due to the need to comply with state law and liability issues. On the other hand, when colocation is not directly on campus, the lack of close proximity poses a real drawback because it does not allow for the kind of valuable informal gatherings that are critical to true interaction. Nonetheless, overall, O2R and R2O has improved greatly at WFOs that are collocated on university campuses; a success story.

STATUS: PITFALLS AND CHALLENGES

Deploying and sustaining observing networks should not be the ultimate goal of ocean and coastal observing systems. From the perspective of NOAA, the federal agency that is the principal target of the special appropriations funds, the true goals of the establishment of these observing systems must include, but not be limited to, improvements in operations and operational forecasting, to support ecosystem management and to document climate changes, leading to the provision of new products and services as proposed in the NOAA SAB NCEP Ocean Modeling Report of 2005 (Pietrafesa et al., 2004). The paper argument for why additional observing systems are needed has been established. We need not revisit those here. However, a blueprint for a rational, well organized, well-coordinated, community wide accepted plan has not been established nor is it being considered by the university community at large. Albeit, the concept of Regional Coastal Ocean Observing Systems (RCOOSs) has evolved and been pushed as the organizational regional unit which should be created and then sewed together at inter-regional boundaries to create the national network. There are eleven of these regional networks. In the face of this emerging opportunity, universities have agreed to form alliances up and down the coasts. But the creation of the sub-regional programs has not yet resulted in associated, conforming systems that are governed by the same rules and thus basically compatible and capable of being seamlessly merged.

One of the pitfalls is that typically one of the first things that a university with traditional marine or ocean sciences academic programs does when it receives special appropriation monies is to immediately expand its infrastructure, with personnel, supplies, and so on. The university may actually decide to establish an observing program and a modeling program, but without any tradition or skill set in those areas it will have to hire technicians and faculty experts from other institutions in kind to build up this capability. Moreover, rather than planning for what should be an up-front commitment to spending a certain percentage of the overall COOS special appropriations to buying the equipment necessary to build and build out whatever array is to be constructed, the institutions may leave this until last; when the money has by and large been spoken for other institutional purposes. These purposes generally do not consider the needs of NOAA; which is basically and fundamentally, getting the 2nd “O” in COOS established.

To appreciate what the agency actually needs to better meet its mission, one must have familiarity with that agency. In the case of the national COOS earmarks, the agency of choice has been NOAA. While an ONR earmark in support of the COOS concept does carry a responsibility for meeting the needs of the operational U.S. NAVY, this implies doing research that is in the NAVY’s interest. However, NOAA is an operational and environmental resource management mission agency and the rationale for a COOS can only be made based on the contribution that the local COOSs will make in building capacity for and enabling NOAA to better meet its mission. Here a familiarity with what the NWS does on land should guide what the COOSs do offshore. First there is the need to define what type of data and information are needed over what spatial scales. To know this one must have knowledge of the processes of fundamental importance to NOAA in the domain of interest. Next is the choice of instruments, platforms, sensors and communications systems. Then one must determine how to actually physically build the array. Next, the process by which vessels are selected, acquired and scheduled must be addressed. Then, complete backup systems must be acquired for replacement at regularly scheduled maintenance cruises and or when there are failures at a specific location. This is a requirement of system performance, all components of which must function reliably and routinely. Finally a data quality assurance and quality control (QA/QC) assessment and modeling architecture must be put in place to evaluate the quality and to then utilize the incoming data in real time.

AN EXAMPLE OF A REGIONAL COOS, DESIGNED WITH THE POTENTIAL TO BECOME A PROTOTYPE REGIONAL COASTAL OCEAN OBSERVING AND PREDICTION SYSTEM, BUT FAILED

In the coastal region of North and South Carolina (the Carolinas), the centerpiece goal of the Carolinas Coastal Ocean Observation and Prediction System (Caro-COOPS) was the routine, and thus "operational", on-line provision of reliable data and readily usable products. These data and products were available on line, via the NOAA GOES and DOD Iridium Satellite systems, and covered present, future and past temporal periods in nested spatial domains and were packaged to include: 1) near real time QA/QC'd data; 2) near real time data driven model information; 3) the prediction of coastal state variables and processes over hours to days; 4) archives of past coastal ocean and atmospheric state variables; and 5) retrospective model event results. Contemporaneous to the creation of Caro-COOPS, the Climate and Weather Impacts on Society & the Environment (CWISE) of the Carolinas program was creating land and ocean based state variable products in the Carolinas in a manner complementary to Caro-COOPS. The land and ocean based CWISE products were merged in a transparent manner with the product data sets. So both CWISE and coastal ocean observing systems were laying the groundwork to incorporate predictions of land based and ocean based meteorological and oceanic state variables into the development of modern, new tools that were intended to provide support to the public, managers, and industry. New data products based on mathematically derived relationships such as winds, waves, water levels, circulation, river discharge, storm surge, flood inundation, and rip-tides were presented. Thus these "COOS" observing systems could rapidly morph into and become "COOPS" observing and prediction systems. That was the visionary concept.

The top priority for Caro-COOPS had been to maintain and sustain the existing network. Optimum operation of existing systems was ensured through regular maintenance, sufficient spare equipment for routine rotations or emergency replacements, and support infrastructure, including ships, warehouse space, and piers. Two turnarounds of the offshore component of the network were done annually. Routine maintenance of the recovered buoys included sensor cleaning to clear fouling and calibration to ensure accuracy, data downloading from the on-site data-loggers, battery replacement, troubleshooting of data-logger and telemetry electronics, and refurbishment of the buoy and mooring components, as needed. A Caro-COOPS (now defunct) mooring is shown in Figure 2a and at the offshore ends of several fishing piers, example of Sunset Beach Fishing pier in Figure 2b; which were both original real-time data delivery system mooring designs at Sea and from a Platform. Plans were to make the mooring single leg and acoustic in data delivery. These systems were different from the conventional NDBC buoy which does not contain an upward looking ADCP nor is capable of collecting directional wave spectra. Here, advancing new technologies, testing new mooring systems, instrument sensors and communications systems in the ocean environment, were considered a proper role for an academic partner to NOAA.

Field inspections of the coastal water level stations (WLS) were done quarterly, with annual maintenance and operation and maintenance of the Caro-COOPS WLS meet all NOAA National Water Level Observing Network (NWLON) standards and in collaboration with NOAA support included performing inspection and acceptance testing of the Caro-COOPS systems, calibrating the acoustic water level sensors, and preparing and configuring the systems for deployment by staff at the Field Operations Division, Chesapeake, VA. It was a well-planned arrangement. A NOAA-approved contractor, Martek, Inc. Scientific Cons, assisted in periodic trouble-shooting and annual maintenance of the WLS systems. Here, academic, federal and industry partners all played key roles.

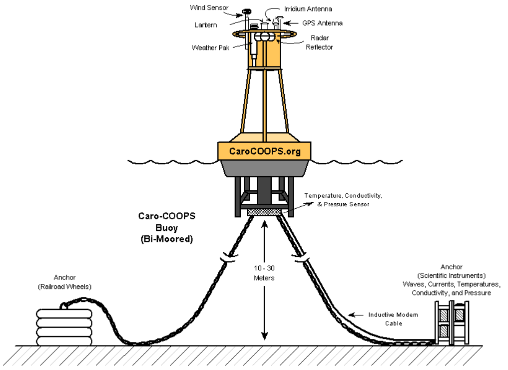


Figure 2a. A prototypical NCSU Caro-COOPS mooring (no longer operational).

Figure 2b. Fishing Pier in Sunset beach NC, where atmospheric and oceanic state variables were collected and visualized on monitors in real-time (no longer operational).

As part of the Caro-COOPS field program, a dedicated test-bed buoy was deployed at a location convenient to get to by ship outside of Charleston Harbor. New sensors and/or systems were being field tested in temporary, short-term deployments of a spare moored buoy. The 1st system tested was an acoustic modem to transmit data from the ADCP to a buoy data-logger. The 2nd system tested was a sea trial of a real time reporting bottom mounted directional wave system. Data from the test instruments are transmitted to the buoy engineering laboratory at NCSU. A comparison of the data from the wave system at the test buoy with waves data from the NDBC Buoy 41004 shows (Figure 3) good agreement in the data despite different technologies and slightly different sampling times (30 minute difference). Given repeated failures and following testing, mechanical wind vane sensors on all of the Caro-COOPS buoy systems were replaced with ultrasonic wind sensors, which have no moving parts and utilize an acoustic time-of-travel principle to determine wind speed and gusts. Integrated with very precise, fluxgate compasses to determine wind direction on a moving platform, it was expected that these modules would perform more accurately and be considerably more robust physically than their predecessors. Additionally, five Fishing Piers in NC, SC and GA were established at CARO-COOPS expense and included air and water temperatures, water levels, wind speeds and directions and waves. The data was collected and immediately sent up hard wires to display monitors in the Pier Houses. The public loved them. Fences were installed around the instruments for security from vandalism and none occurred over a several year period. This data filled a partial void between offshore NDBO Buoys and CMAN stations. Plus many Fishing Piers are in the vicinity of the genesis of mid-latitude storms. All of these test-bed facilities were viewed as constituting a proper role for a university partner of NOAA.

NCSU studies showed that air-sea flux data can detect the onset or intensification of winter-time extra-tropical cyclone (ETC) events. As seen in Figure 4, data from a built-out Caro-COOPS array (the region of no existing red-pins) would give warning of the onset and be assimilated into coupled atmosphere-ocean models already running at NCSU. NCEP needs more data from the data-starved Carolinas, the epi-center of cyclogenesis on the U.S. eastern seaboard. This finding could then be shared with NOAA NCEP and NOS to build the case for a denser monitoring network as a part of IOOS. Moreover, as part of CWISE, a new operational storm genesis or intensification detection tool was being developed and once completed, would be transferred to regional NOAA NWS WFOs. Again, this type of experimental coupled modeling is a proper role for university partners with NOAA.

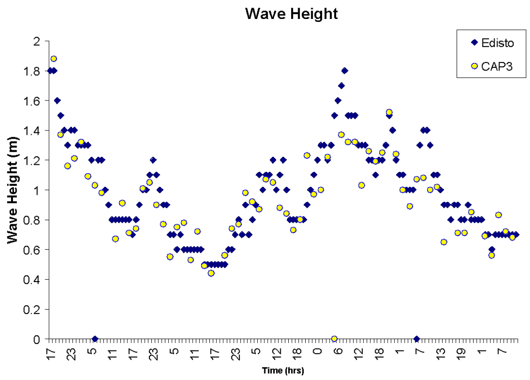


Figure 3. Wave height data comparison of the Test showing Caro-COOPS Mooring and NDBC Buoy 41004 May 11-17, 2006

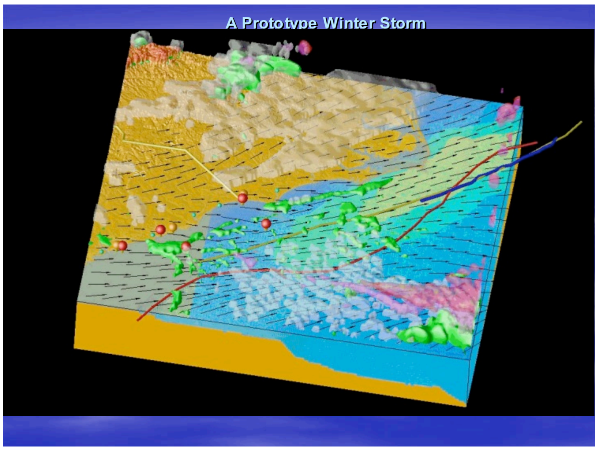


Figure 4. NCSU ETC model output assets and prime region of cyclogenesis in the Carolinas (Jacobs et al., 2023)

The initial demonstration of the real-time interdisciplinary forecast concept for Caro-COOPS had been the NCSU based real-time prediction and analyses of storm surge, flooding, and inundation in advance of and during the passage of coastal storms. At the new UCAR enabled modeling and visualization Lab located at CCU, this effort will continue and is expected to improve warnings and provide local officials with the information needed for mitigation, preparedness, and prevention measures prior to and during storm events. CCU has developed and is continuing to develop an interactively coupled atmospheric-land-oceanic numerical model that will be utilized to run routinely and will create "% probability of flooding and inundation maps", a product in advance of a hurricane making landfall and thereafter as flooding occurs inland and upland; a new tool for emergency managers and WFOs created by an academic partner.

In 2003 the Director of the NWS requested an external review of the Meteorological (later Atmospheric) Techniques Laboratory (M/ATL) in Silver Springs MD. The M/ATL was charged with developing new technological widgets to aid and abet operational forecasting from within NOAA. The outcome of that shelved study was the discovery via the External Review Team that the product of Model Output Statistics (MOS) based on multiple NWS numerical model runs, was far more accurate than any single deterministic run, from 1 hour out to 5 days at all of the WFOs. This was a shocking revelation to the NWS, which basically did not possess internal statistics expertise, and given the potential for a call for a reduction in force and a backlash from the NWS Union of Forecasters, the report was shelved. However, the Caro-COOPS PI knew about this revelation and proposed that MOS be introduced into NOAA models of coastal flooding during the passage of hurricanes. To prove the point, a study of MOS applied to the flooding following the landfall of Hurricane Hugo onto Charleston SC in 1989 was studied (Pietrafesa et al., 2004) and the results (Figures 5 left, right panels) demonstrated that a time sequenced PEF iso-lines of the "percent (%) probability of flooding from 0 to 100", updated via model runs every 6 hours with updated NOAA NWS NHC storm location and intensity, provided the best flooding information.

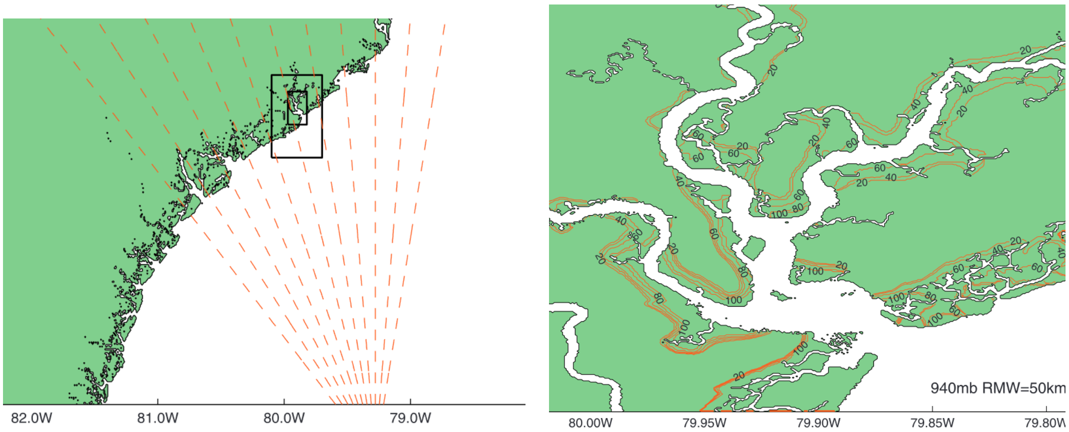


Figure 5. left panel, an incoming, land-falling hurricane, such as Hugo in 1989 at Charleston SC; right panel, % probability of flooding of the Charleston domain at time of landfall.

One of the critical challenges in Caro-COOPS had been in providing wave field information in near real time, as well as model forecasts, which are so important for commerce, fishing, and recreation in the region. Therein the scientists focused on four separate efforts: conducting wave field modeling during the passages of hurricanes; making wave forecasts in the presence of varying waves over variable topography; making wave forecasts in the region of the Gulf Stream Front and beyond, and providing wave information as both “now-casts” and “forecasts” across the Carolinas domain and at specific locations. Advances had been significant for each. Caro-COOPS scientists also attempted to utilize actual observations of the wave field using bottom mounted ADCPs that measured the wave field as an outcome of its interactions with the current field to forecast future wave conditions. To properly predict the wave field, they found that they had to analyze the effect of currents on waves, the effect of waves on currents and surge, and the interactive coupling between them. Figure 6 shows the change in inundation due to including waves in the NCSU/CCU model system and Figure 7 shows the goodness of NCSU/CCU wave forecasts made directly from the data. The next step was to utilize these data to separate out those data that are linked to the formation of dangerous Rip Tides so that they could advance the state of the NOAA NOS Rip Tide forecast system for regional NWS WFOs, which has real value to the public at the beaches. The wave forecasts at the NDBC sites nationally were made operationally available from NCSU to NOS, in 2001. However the capability was canceled when the Caro-COOPS funding was terminated in 2007 when NOAA funding was terminated. Unfortunately, NCSU did not have a Legacy Earmark. Nonetheless, the wave forecast capability demonstrated that university based statistics, which is not an institutional strength of NOAA could contribute to NOAA’s operational forecast capability, in real-time; a proper role for a university NOAA partner.

The three-dimensional (3-D) coupling system developed at NC State included the then 3rd generation wave model (SWAN) and current model (POM), includes the wetting and drying scheme of Peng et al (2005) which was set up and validated in the field by a NWS field team from the Charleston WFO.. The validation of the complete model system output was conducted in Charleston Harbor, South Carolina. Figures 8 left panel and 8 right panel show the effect of wave-current interaction on storm surge. The simulated storm surges by the wave-surge coupled model at the NOAA coastal observing sites are more accurate than those simulated by the surge and inundation model (without interactively coupled waves and currents) as compared with the NOAA observational data (asterisks wherever observations are available).

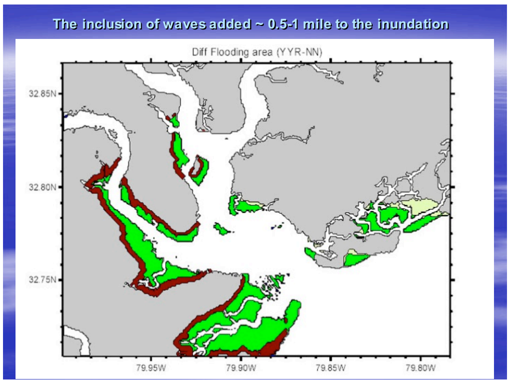


Figure 6. Change in inundation at Charleston sites during the passage of Hugo in 1989.

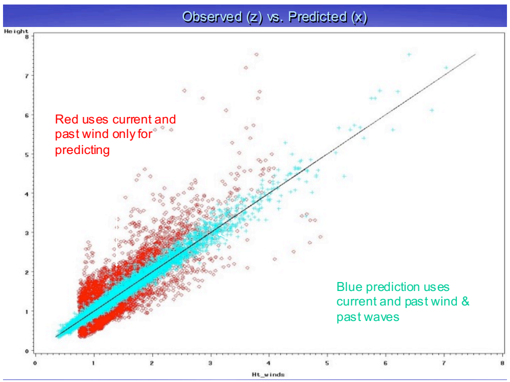


Figure 7. Forecasting waves at coastal observing Sites using past and present wind and wave data. These wave forecasts became operational at all NDBC sites nationally.

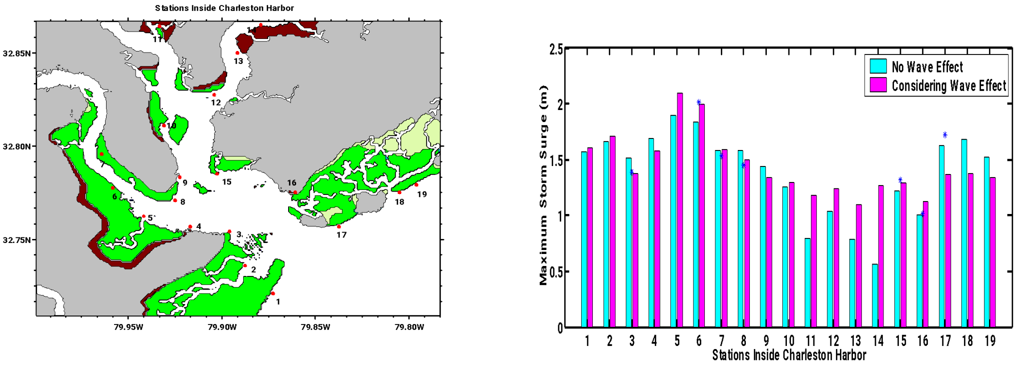
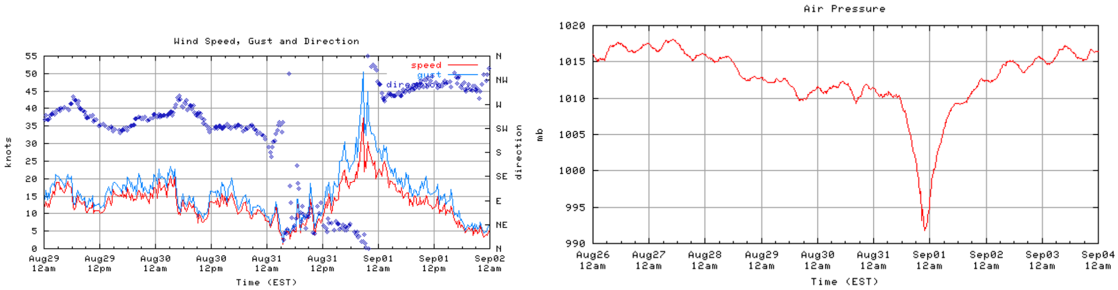


Figure 8. left) Locations in the study area, with data used to plot the peak surges in the right panel; right) Peak storm surges at the locations shown in 8 left without considering gravity wave effects (green), considering wave effects (red), and observational water levels (asterisks)

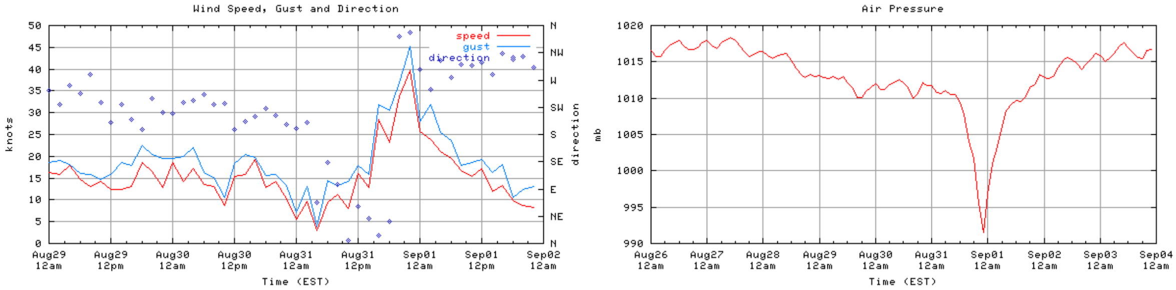
Another proper role for university partners of NOAA's is in testing sensor systems during the passage of storms. Unattended oceanic moorings were generally untested under severe storm conditions. Both university and NOAA staff make every effort to test sensors under different circumstances but storms at sea present new challenges. Both NOAA and university scientists need to understand whether or not their mooring designs can withstand storm waves and currents and whether or not sensors can handle the abuse. The issue of course is that Eulerian oceanic moorings could be subjected to extreme waves and currents under storm conditions and may not survive. As such, moorings should be designed to withstand high waves and energetic currents. Otherwise there would be no documentation of the response of in-situ state variable conditions at sea, nor of sensor sustainability under storm conditions.

As it occurred, Hurricane Ernesto, the first hurricane of the 2006 Atlantic hurricane season, crossed southern Florida and emerged into the Atlantic near Cape Canaveral early on August 31 2006. While heading northeastward, Ernesto was just below hurricane strength, with maximum sustained winds near 70 mph, when it made landfall again near Long Beach, NC at 11: 30 PM EDT on August 31. Wind and barometric pressure data recovered from NCSU Caro-COOPS stations offshore of Sunset Beach NC before and after passage of the storm are shown in Figures 9, 10 and 11. Note in Figure 9 the sharp drop in wind speed and shift in direction as Ernesto's eye passed over the Sunset Beach 30 meter station. Another R-COOS array that mimicked the Caro-COOPS array, chose to shut their data reporting system down as they were worried about “bad data”. They had backgrounds in the “wet” sciences and thus had no training in the role of universities in operational forecasting. They did not appreciate the importance of how difficult it is to obtain storm data nor of the need to test mooring designs and instrument integrity. They also had no appreciation of the goal of operational forecasting. Starting around September 4, the Caro-COOPS mooring systems came back on-line and updated buoy information began to be delivered to the NCSU server. By September 8, the system was providing regular updates again.



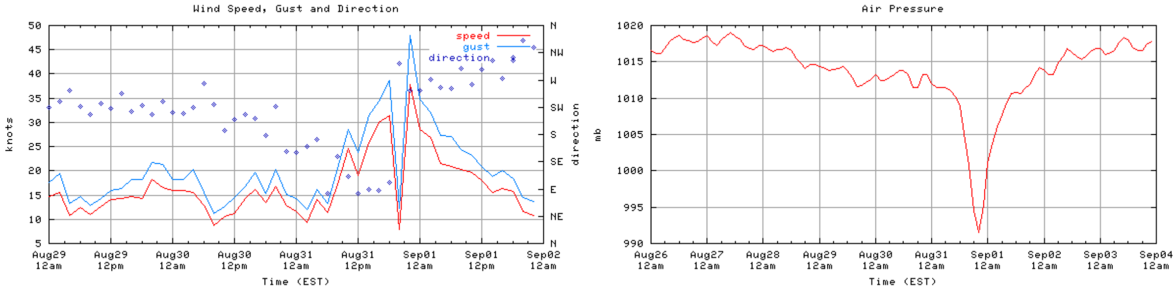
(a) **(b)**

Figure 9. Wind direction and speed (a) and barometric pressure (b) at coastal station Sunset Beach 1 in 30 meters of water, during passage of Hurricane Ernesto.



(a) **(b)**

Figure 10. Wind direction and speed (a) and barometric pressure (b) at moored buoy station Sunset Beach 2 in 45 meters of water during the passage of Hurricane Ernesto.



(a) **(b)**

Figure 11. Wind direction and speed (a) and barometric pressure (b) at moored buoy station Sunset Beach 3 in 75 meters of water during the passage of Hurricane Ernesto.

DATA ASSIMILATION: THE DEVELOPMENT OF 4-DIMENSIONAL DATA ASSIMILATION SYSTEM BASED ON THE PRINCETON OCEAN MODEL AND ITS APPLICATION ON STORM SURGE SIMULATION

In the past half a century, although improvements have been made in numerical prediction of storm surge and coastal ocean circulation, substantial prediction errors still exist. Numerical ocean predictions are never exact solutions of the real world ocean. Instead, they are only an approximation of the real ocean both in terms of dynamics and physics (Pietrafesa et al., 2004). The errors or uncertainties of model prediction come from two main sources: 1) dynamical simplifications and physical parameterizations; and 2) initial and boundary conditions. Therefore, oceanic prediction can be improved either by improving the dynamical approximations and physical parameterizations or by improving initial and boundary conditions. With the development of large ocean observing systems and remote sensing techniques, more and more oceanic data are becoming available. This provides a promising prospect for improving the model initial conditions through data assimilation. Among all data assimilation methods, 4-dimensional variational data assimilation (4D-Var) is one of the most effective and powerful approaches developed over the past two decades. It is an advanced data assimilation method that involves the adjoint technique and has the advantage of directly assimilating various observations distributed in time and space into the numerical model while maintaining dynamical and physical consistency with the model. Its fundamental concept is to seek to produce an analysis which minimizes a given measure of the "distance" to the observations, while at the same time satisfying an explicit dynamical constraint (as schematically shown in Figure 12).

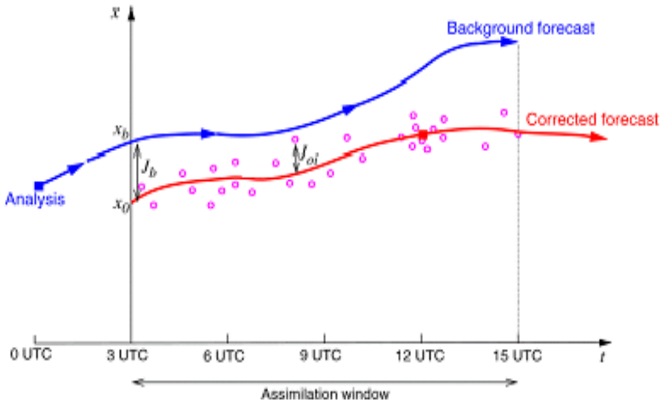


Figure 12. Schematic illustration of 4D-Var

At the time of the Caro-COOPS program, a case was made to NOAA line office administrators (AAs) to begin using NOAA data for more than its National Centers for Environmental Prediction (NCEP) operational forecast predictions. NOAA's AAs agreed and NCEP commissioned a study to evaluate what NCEP should be doing with the fire hose of data being downloaded daily by NOAA, for basically no reason other than for NCEP model validity. The report (Bosart & Pietrafesa, 2001) strongly recommended that NOAA data streams and assets be evaluated for NCEP model improvement. At that time the NOAA Administrator was a PhD in Mathematics and strongly endorsed the recommendation that data be assimilated into the NCEP models to test for model forecast improvement. However NCEP did not have an in-house Data Assimilation (DA) specialist, and the Caro-COOPS NC State numerical modeling team took on the challenge. The NCSU numerical model team developed a 4D-Variational (4D-Var) scheme based on the 3-dimensional Princeton Ocean Model (POM) with an inundation scheme. The development of the 4D-Var system was an arduous job, which included the development of tangent linear model, the development of adjoint model and finally the setup of the 4D-Var with minimization algorithm. This 4DVAR data assimilation system is able to assimilate the real time data from the satellites, radars, ships, buoys, ground-based stations, etc. Therefore, the setup of the 4DVAR data assimilation system at NCSU made a great contribution in improving the forecasts and analysis of the ocean state.

A Tangent Linear Model (TLM) provided a first-order approximation to the evolution of perturbations in a nonlinear forecast trajectory. A TLM model consists of tangent linear equations, and maps a perturbation vector, δ x (t=1) = L δ x (t=0), from initial time t0 to forecast time t=1. Here, L is the tangent linear operator and x is the model state vector. Thus it is very useful in the sensitivity study of the forecasting errors to the initial errors. It can also be used in the predictability study of the ocean or the atmosphere. The most important value of TLM is its application in the incremental 4-dimensional variational data assimilation (4DVAR), which employs the TLM in its inner loop to evolve the initial perturbation forward in time and calculate the cost function measuring the distance between the model and the observation. Also, an adjoint (inverse) model using in 4DVAR is developed based on the TLM, so TLM is the prerequisite to developing an adjoint model. Therefore, the development of a TLM for POM has great value for further oceanographic research. A tangent linear model (TLM) of the 3-dimensional Princeton Ocean Model (POM) with an inundation scheme was first developed at NCSU. TLM is a model, comprising tangent linear equations, that maps a perturbation vector, x(t=1) = L x(t=0), from initial time t=0 to forecast time t=1 Here, L is the tangent linear operator and x is the model state vector. This TLM of POM developed contains the linearized dynamical and physical process of the ocean. The correctness of TLM is checked through very strict Taylor Expansion criteria.

The adjoint (inverse) model of the 3-dimensional Princeton Ocean Model (POM) with an inundation scheme was then developed based on the tangent linear model of POM. The adjoint model is the inverse counterpart of the tangent linear model. The original POM runs forward in time (thus it is also called the "forward" model), while its adjoint model runs backward in time. In the other words, the original POM predicts the ocean state in the future according to the present/past ocean state while its adjoint model deduces the ocean state in the past from the present/future ocean state. Developing an adjoint model is even more challenging and difficult than developing a tangent linear model, since it requires very careful programming and extensive knowledge of the physical dynamics that are incorporated in POM. The NCSU development was the first time that an adjoint model of the 3-dimensional POM had been developed successfully, although the original POM is a very famous ocean model and has been widely used in the research and operational prediction of the ocean state. The POM adjoint model developed at NC State can be used in 4-dimensional variational data assimilation which requires forward and backward integration of the ocean model, sensitivity analyses of model forecasting errors, development of adaptive observing strategies, and so on. Thus, the POM adjoint model is very valuable and is a great contribution to our NOAA-supported project as well as to the general oceanographic community when it passed the muster of NCEP and was released to the public.

The 4D-Var system is composed of a forward model, an adjoint model and a minimization algorithm. The forward model is used to calculate the basic state of the variables for the adjoint model and the cost function that measures the distance between the model output and the observations. The adjoint model is used to calculate the gradient of cost function with respect to the initial condition (IC) or boundary condition (BC). A minimization algorithm is then employed to find an optimal IC or BC which minimizes the distance between the model output and the observations. The optimized IC or BC can then be used to make an optimal forecast and a best analysis of the ocean state which combines the model dynamics and observations. Limited-memory quasi-Newton method is employed in the minimization of the cost function. In general, this 4D-Var system is able to assimilate various types of data from satellites, radars, ships, buoys, ground-based stations, etc. To evaluate the performance of this 4D-Var system, a set of Observing System Simulation Experiments (OSSEs) were conducted by assimilating the model-produced water level and current to see the impacts on storm surge simulation.

In the first set of experiments, the 4DVAR data assimilation system based on POM was applied to a storm surge case along the United States East Coast during hurricane Hugo, Sept. 21-22, 1989. The “pseudo-observations” generated by a high resolution model were used. Using “pseudo-observations" in data assimilation studies has the advantage of providing a full suite of balanced datasets which can be assimilated into the forecast model. The same wind field was used to generate the “pseudo-observations” and the storm surge forecast, so the uncertainty associated with the wind forcing was minimized. This allows us to focus on the effect of determining initial conditions on storm surge. The experimental results demonstrate that the 4D-Var data assimilation based on the developed POM adjoint model is able to find an optimal initial condition for the storm surge forecasting, with the values of the cost function which measures the difference between the model and “observations" reduced rapidly during the first 10 minimization iterations. Improvements on water level prediction are obtained both within and several hours beyond the assimilation window by assimilating water level observations alone or assimilating both water level and surface current observations. Figure 13a shows the water level field from the “observations” and each experiment at 01z Sept. 22 which is out of the assimilation window. Compared to the “observations” (Figure 13a), the control run without data assimilation (NoDA, Figure 13b) under-predicts the water level along much of the coastline north of the Georgia-Carolina border. After assimilating the water level (Figure 13c), the height of the water level over this area increases and is closer to the “observations". Assimilating both water level and surface current (Figure 12d) has similar results as but slightly better than assimilating only water level. Figure 14 shows the time series (starting at 21Z Sept. 21) of the root mean square error (RMSE) of water level averaged over all ocean grid points for each experiment with respect to the “observations” of water level. The model forecasting errors are reduced significantly by data assimilation within and a few hours beyond the assimilation window, with DA-2 slightly outperforming DA-1. However, the effect of data assimilation outside the assimilation window decreases as forecast time increases.

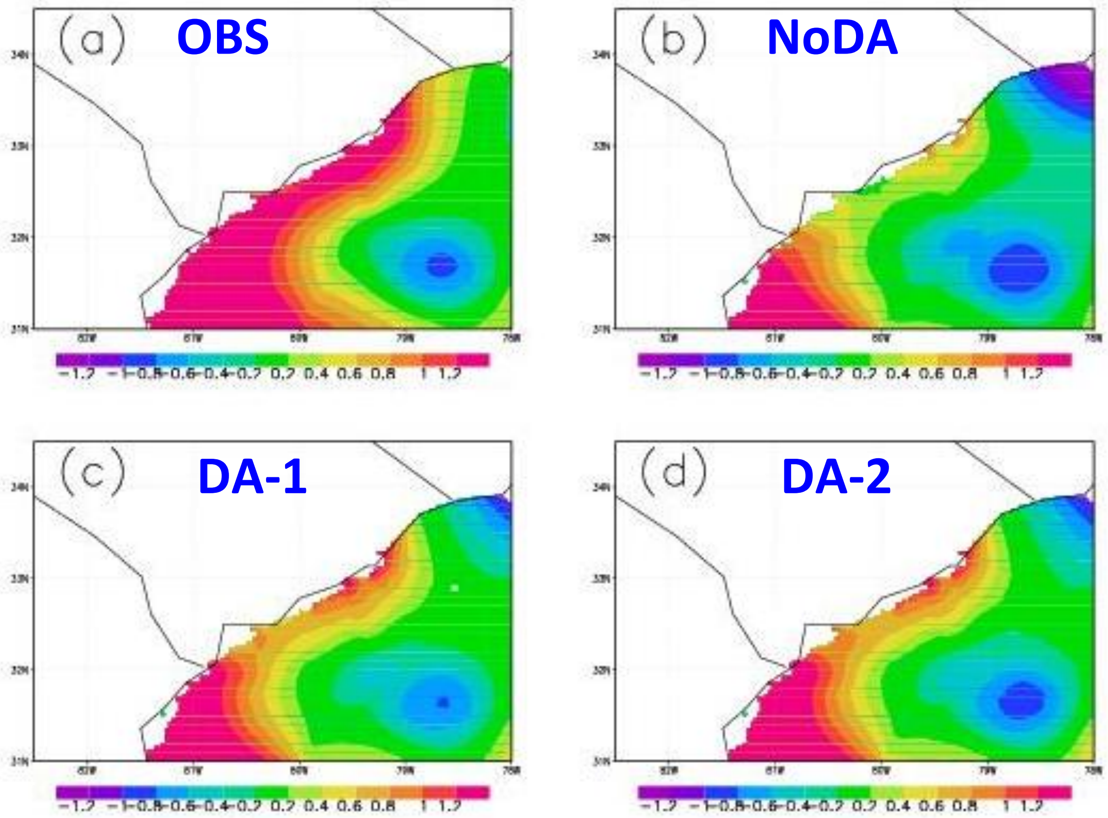


Figure 13. The water level fields at 01Z Sept. 22 from (a) pseudo-observations; (b) NoDA; (c) DA-1 and (d) DA-2 (unit: m)

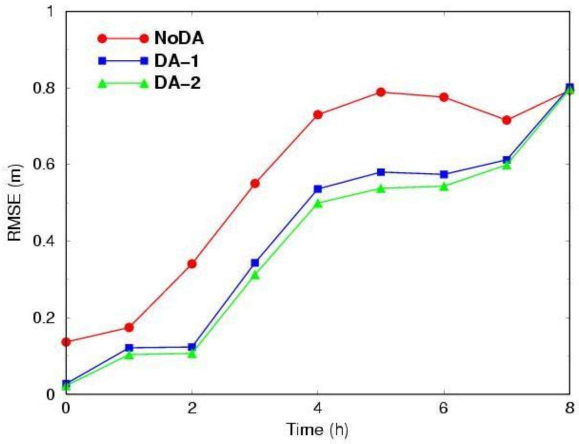


Figure 14. Time series of the root mean square error (RMSE) of water level averaged over all ocean grid points for each experiment with respect to the pseudo-observations of water level starting from 21Z Sept. 21 to 05Z Sept. 22 (unit: m).

The maximum height of the peak storm surge along the coast is often the quantity of interest during the threat of a tropical cyclone. Figure 15 shows the peak surge at 17 locations evenly distributed along a line parallel to the coast for the "observations" and each experiment. It indicates that data assimilation produces significant improvements in the estimation of peak surge along the southern section of line AB, but no improvement on the northern section of the line. It is worth noting that although the storm surge predicted by the stand-alone POM without data assimilation produced large errors north of 32ºN as shown in Figure 14, it is able to capture the peak surge that occurred near location 12. As a result, the improvement in peak surge is small near location 12. The large error in peak surge that occurred near the northern boundary (locations 15-17) is not effectively reduced by data assimilation. The error in this region is apparently less sensitive to initial conditions. This could be a result of model deficiencies, such as the lower resolution, the lack of an inundation/drying scheme, and the fixed lateral open boundary conditions for the vertical mean 2-D current.

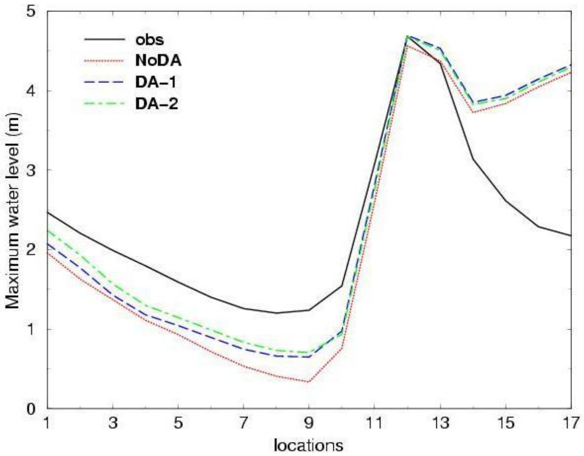


Figure 15. Maximum height of water level along the coast, the pseudo-observations and each experiment (the number 1 in X-axis corresponding to the most southern location and 17 corresponding to most northern location. unit: m).

Figures 16 a-b show the surface currents from the “observations” and the control run (NoDA) and Figures 16 c-d show the differences of surface currents between the data assimilation experiments and the control run at 00z Sept. 22. A strong vortex over the southeast corner of the domain and a southwest current along the eastern coast are seen in the “observations” (Figure 14 a). In the control run (Figure 14b), however, the surface currents along the eastern coast are opposite to that of “observations” and the vortex over the southeast corner is weak. Assimilating only water level (Figure 14c) or assimilating both water level and surface current (Figure 14d) intensified the vortex and produced onshore currents which led to an increase in the water level along the coast.

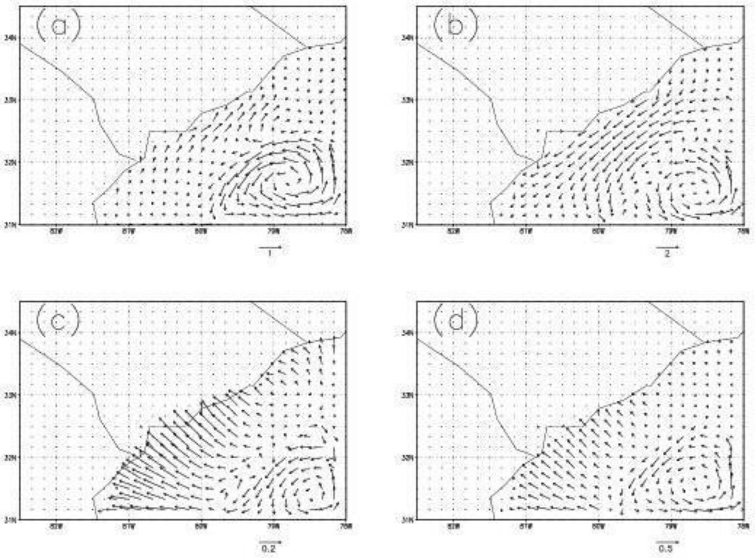


Figure 16. Refer to the text.

The experimental results showed that using 4D-Var to correct the errors in the initial conditions can improve storm surge forecasts. However, the errors in boundary conditions, especially in the upper boundary conditions such as the surface wind stress, may still lead to significant errors in storm surge prediction that cannot be effectively reduced by correcting the initial conditions. Thus correcting the errors in the upper boundary conditions during data assimilation may be as important as correcting the errors in the initial conditions. Therefore, in this study, identical twin experiments were performed to explore the effects of correcting the errors in the upper boundary Figure 16: (a) the surface currents of "pseudo-observations"; (b) the surface currents from the NoDA simulation; c) the differences of surface currents at 00Z Sept. 22 between DA-1 and NoDA; (d) same as (c) except of DA-2 minus NoDA (unit: m/s).

Since the observed radius of maximum wind (R_{MW}) is not available for most hurricane cases, maximum wind (R_{MW}) is not available for most hurricane cases, considerable errors may exist in the estimate of R_{MW}. The uncertainty in R_{MW} would cause errors in the calculation of the surface wind stress and lead to bias in storm surge simulation. Thus R_{MW} was selected as the control variable and adjusting R_{MW} is identical to adjusting the upper boundary conditions. 4D-Var experiments were performed to estimate the value of R_{MW} by assimilating pseudo-observations (model-produced) of water level into the model.

We selected a storm surge case associated with Hurricane Charley 9-14 August, 2004 (Figure 17). The study focused on a small area of the coast along Georgia, South Carolina and North Carolina during a 12-h period starting at 0500 UTC 14 August.

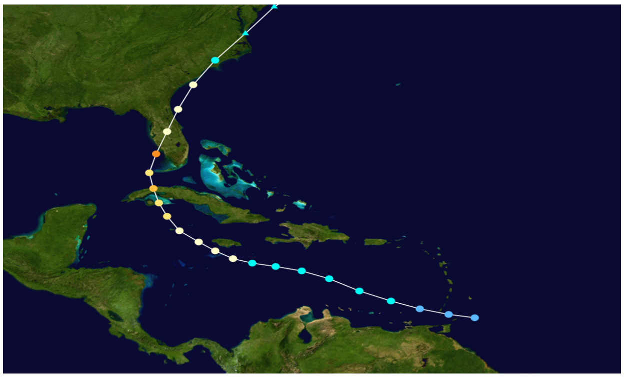


Figure 17. The track of Hurricane Charley (9-14 August, 2004)

To make it closer to the real situation for storm surge forecasts, two more realistic twin experiments were designed by adding random errors into the pseudo-observations and including a background term in the cost function as well as assimilating the pseudo-observations of water level only on a small number of observations along the coastal ocean: 1) DA_26obs: assimilate pseudo-observations of 26 sites evenly located along the coastal ocean including the 10 water level stations, and 2) DA_10obs: assimilate pseudo-observations of the 10 NOAA NOS and Caro-COOPS water level stations. We assumed the control run (denoted as ErICBC_NoDA) has errors in both the initial conditions and wind stress by adding random errors into them. The results indicate that the errors in surface wind stress can be effectively corrected by 4D-Var data assimilation and thus the accuracy of the storm surge forecasts is improved significantly. The results also show that, if the forecasting errors are attributed to both incorrect initial conditions and incorrect boundary conditions, then adjusting both the initial conditions and the boundary conditions is the best way for 4D-Var to improve storm surge simulation. Figure 18 shows the RMSE and SDE averaged over all ocean grid points for the control experiment and 4D-Var experiments. Although no reduction of RMSE or SDE is seen in the initial time for both the data assimilation experiments, the reductions of RMSE and SDE are significant between 2nd and 12th hour, implying that the reductions of RMSE and SDE on the whole domain are mainly caused by the correction of errors in the surface wind forcing by data assimilation (this is consistent with the fact that the surface wind forcing is the primary factor causing errors in the storm surge forecasts). The results from the two data assimilation experiments are similar with DA_26obs slightly outperforming DA_10obs (indicating that more observations lead to more improvements in the simulation of water level by data assimilation).

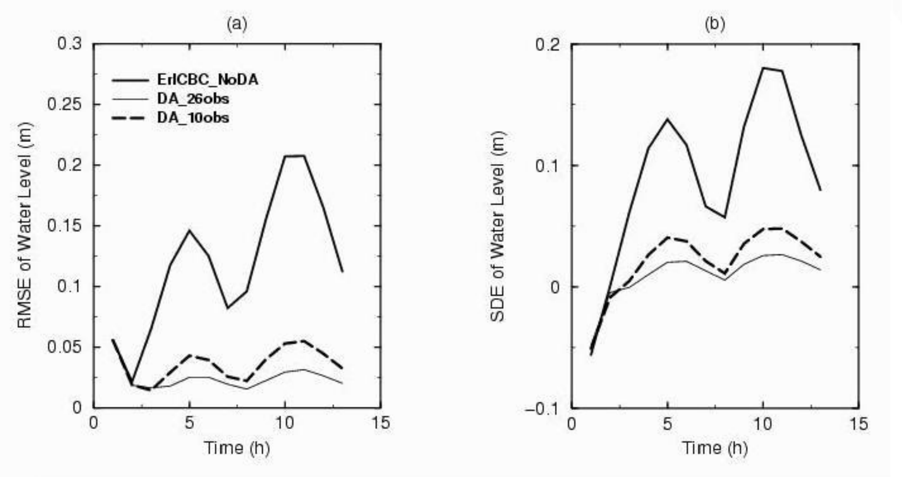


Figure 18. (a) The root mean square errors (RMSE) and (b) standard deviation errors (SDE) of 12-h simulation of water level with respect to the pseudo-observations averaged over all ocean grid points for ErICBC_NoDA, DA_26obs and DA_10obs.

The RMSE, SDE and cross correlation for the time series of the 12-h simulated water level from control run and DA_26obs are calculated on each ocean grid point and their differences (DA_26obs minus control run) are shown in Figure 19. Significant improvements (negative values of differences for RMSE or SDE and positive values of differences for the cross correlation) are seen along the coastal area after data assimilation. Figure 20 shows the water level fields from "observations", control run and DA_26obs in 1400Z 14 August. One can see that the false prediction of the high water level over the northern coastal area and the low water level over the southern coastal area of South Carolina is corrected effectively by the data assimilation. The maximum and minimum values of water level in the coastal area are important quantities in the storm surge forecasts which the government or agency and local residents are most concerned about. Figure 21 shows the maximum and minimum values of water level on the 26 observation sites (along the coast from south to north) during the 12-h forecast period for observations, control run and DA_26obs. Compared to the control run, the DA_26obs matches:

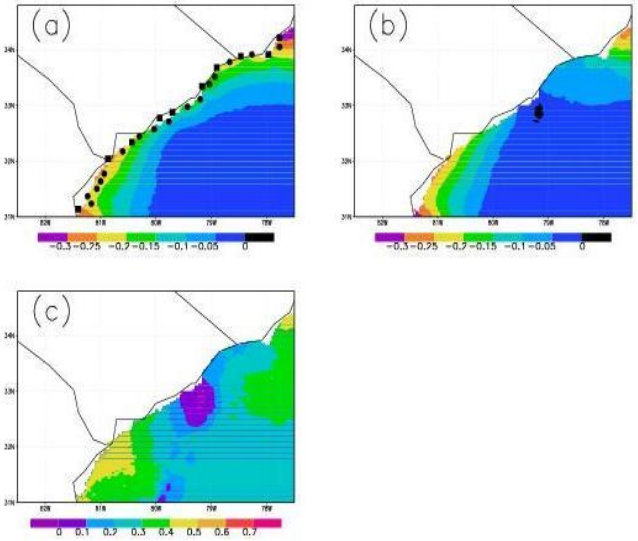


Figure 19. The differences of (a) root mean square errors (RMSE), (b) standard deviation errors (SDE) and (c) cross correlation for the time series of the 12-h simulated water level water level at each ocean grid point with respect to the pseudo-observations for DA_26obs. The solid circles and solid squares in (a) represent the locations of the selected 26 observations including the 10 existing water level stations (solid squares).

The experiment results of the Caro-COOPS DA numerical model demonstrated that the 4D-Var data assimilation based on the developed POM adjoint model was able to find an “optimal” initial condition or upper boundary conditions (wind stress) for the storm surge forecasting. Improvements on water level prediction are obtained both within and several hours beyond the assimilation window by assimilating water level “observations” alone or assimilating both water level and current “observations”. The added benefit of assimilating both water level and surface currents is relatively small since water level and current fields are adjusted in dynamical and physical consistency with the constraint of the model control equations and the cost function. The results also indicated that if the forecasting errors are attributed to the incorrect initial conditions, adjusting the initial conditions by setting the initial conditions as control variables is effective for 4D-Var to improve storm surge simulation. The same conclusion is reached when the forecasting errors are attributed to the erroneous upper boundary conditions. It does not work for 4D-Var to adjust the wrong source of errors to improve storm surge simulation. If the forecasting errors are attributed to both incorrect initial conditions and incorrect upper boundary conditions, then adjusting both the initial conditions and the upper boundary conditions is the best way for 4D-Var to improve storm surge simulation. In practice, however, it is usually unclear whether the forecast errors are caused by the errors in the initial conditions or in the upper boundary conditions. Therefore, it would be safe and effective to use both the initial conditions and the upper boundary conditions as control variables. On the other hand, the errors in the wind stress may have larger and longer impacts on the storm surge simulation than the errors in the initial conditions. Considering the fast convergence rate of correcting the errors in wind stress (only a few iterations are needed), it may be efficient to correct only the errors in wind stress for the mid-term or long-term (say, longer than 6 hours) forecasts of storm surge. Furthermore, besides the estimate of R_{MW}, other parameters in the calculation of wind stress such as the drag coefficient C_d can also be estimated through 4D-Var for each specific storm surge case. More improvement in storm surge simulation is expected since the estimation of these parameters through 4D-Var may give a more accurate calculation of wind stress.

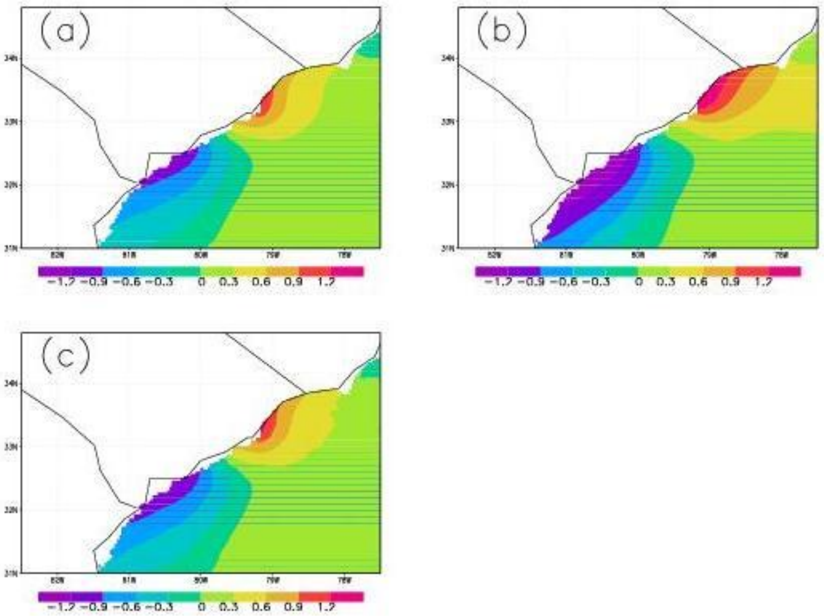


Figure 20. The fields of water level from (a) pseudo-observations; (b) ErICBC_NoDA; (c) DA_26obs at 1400 UTC 14 August (unit: m).

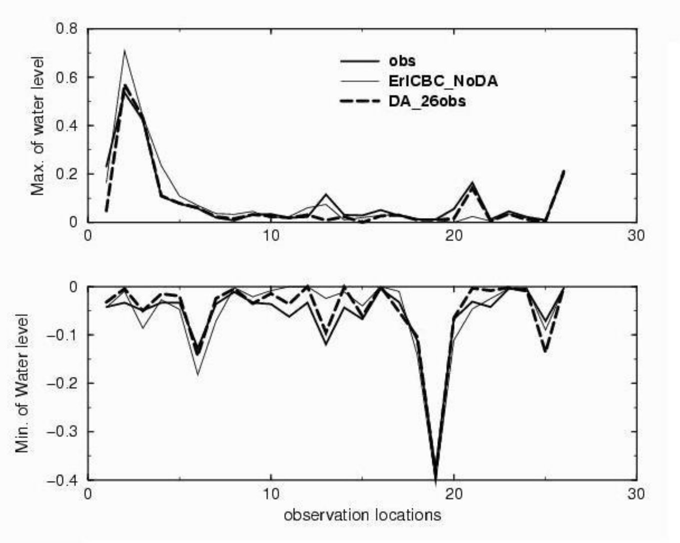


Figure 21. The maximum (upper panel) and minimum (bottom panel) values of water level on the 26 observation sites (along the coast from south to north) during the 12-h forecast period for observations, control run and DA_26obs.

It is noteworthy that, in the above experiments, the track and intensity of hurricanes or tropical storms predicted by the NOAA National Hurricane Center (NHC) is assumed to be correct and fixed during the data assimilation as well as the afterward storm surge simulation using optimal IC or BC. It is possible that the changes in the track and intensity of hurricane may overwhelm the optimal estimate of R_{MW} by data assimilation. Therefore, the value of R_{MW} should be updated according to the latest forecasts of the track and intensity of hurricanes or tropical storms. The same thing should be done to C_d if estimated by data assimilation. It is also worth mentioning that the results obtained in this study are based on the idealized situations: 1) the water level data used is model-produced and 2) the model is assumed to be perfect. In reality, the water level observations are only available on sparse spatial network of coastal and shelf water level stations and may contain various noises or errors such as the instrument error, representativeness error and processing error (e.g., interpolation error), and the model is not perfect due to the dynamical simplifications and physical parameterizations. It is possible that the erroneous and sparse observations as well as the imperfect model may lead to the failure of finding the "true" (or "optimal") initial conditions or upper boundary conditions. That is the major reason why the improvement of storm surge is marginal when we tried to assimilate the real water level data which only had 8 stations available for the Hurricane Hugo and Charley cases. Therefore, this study may be considered as a theoretical and preliminary study of correcting the initial conditions and upper boundary conditions in storm surge simulation by 4D-Var approach. As to correcting the errors in wind stress through 4D-Var, more experiments should be made to deal with some unclear issues before it is applied in practice, for instance, adjusting which parameter in the calculation of wind stress is appropriate and has the best effect for specific storm surge case, how to make a balance between the adjustments of these parameters if all of them are simultaneously estimated, and what else data besides the water level can be used for the estimation of these parameters, etc. Furthermore, the calculation of the background error covariance is very important and is still an open issue in data assimilation. In this study, only approximated variances based on the maximum differences between a 12-h model run and the initial condition are included in the background error covariance matrix. Although this method has been used in many studies and is proven to be a simple but effective method for estimating background error covariance in 4D-Var, a more comprehensively designed background error covariance based on the long-term statistics of the standard deviation cross correction of the model variables may be used in real application, which will enhance the effectiveness of the minimization procedure and the positive impacts of data assimilation on the model forecast.

Besides the application in storm surge simulation, the 4D-Var system based on POM was applied to many other fields of oceanic research, such as the adaptive (targeted) observations, inter-seasonal or inter-annual prediction of ocean status and analysis of climatologic ocean temperature/salinity. So, had Caro-COOPS continued, NCSU scientists could have used the 4D-Var system based on POM to assimilate observational data from satellites, such as the TOPEX/Poseidon sea surface height, NOAA's POES sea surface temperature and NASA MODIS ocean color, to evaluate the impacts of these data on the long-term prediction or analysis of the ocean. The adjoint model developed via the NOAA Caro-COOPS program could also have been used in the study of adaptive or "targeted" observations. Adaptive observation strategies (AOS) aim to improve forecasts by adding additional observations at a few locations that have no standard observations. The adjoint model can be used to determine the region where the quality of the initial conditions has the largest impact on the forecasting errors of the whole domain. Thus the observation platform or network would be most effective or economic for improving the forecasts if they are put on these "sensitive" regions.

In order to evaluate the correction of errors in Initial Conditions and the specified Wind Stress in Storm Surge Simulation Using an Adjoint Optimal Technique, two realistic and comprehensive data assimilation experiments were conducted in which a background term is included, only a small number of observations along the coast are assimilated, and random normal errors are added into the observations. The background error covariance is set to be a diagonal variance matrix based on the maximum differences between a 12-h model forecast and the initial state. The observation error covariance was set to be a diagonal matrix with the main elements being the variance of the random normal errors added to the observations. We assume that there is no spatial correlation between the variables in the background error covariance and the observation error covariance. The following figures show the preliminary results of this research. Figure 22a is the "observation" (from GFS output) of large scale (0-1 waves) v-component at 12 UTC Jan. 1, 2007, Figure 22b is the Weather Research Forecast (WRF) model forecast without data assimilation and Figure 22c is the result after the "observation" of large scale v-component was assimilated into WRF using WRF 3DVAR. It can be seen that the large scale information from the global model can be incorporated into the regional model forecast through data assimilation. However, a great deal of work remains before the issue can be more fully addressed and properly resolved. The DA experiments conducted by Caro-COOPS scientists (Jacobs et al., 2023) is a proper role by a university partner, so that NCEP, which is charged to be "operational" 24/7/365, does not have to. This is a way for new modeling capabilities to "cross the valley of death" (Pietrafesa & Buckley, 2007).

What is demonstrated herein is that universities and NOAA can have a rigorous relationship. Universities can develop the 'R" if they know what is needed for the "O". The good news is that several universities now offer undergraduate curricula in either or both atmospheric and ocean sciences and they would only have to agree to begin offering new courses in operational ocean forecasting. UCAR and its COL may want to promote this nationally amongst its member institutions. Clearly future NOAA NWS WFOs will need to have forecasters familiar with coastal weather given the population density in coastal zones, which now consists of nearly half of the total U.S. population. Further as the ability to forecast more environmental state variables advances, real time environmental data will become a necessary commodity and forecasters skilled in the ocean sciences will need the data and information. Likewise, to predict the impacts of past events, lodged in the historic record on todays and tomorrow's human altered systems requires in-depth knowledge of the bio-geo-chemistry of those systems. So there is a compelling case to be made for changes to be made in university curricula in the ocean and marine sciences (and more broadly the ecosystem/ecological sciences) that would support the needs and demands of the emerging ocean and coastal observing systems and networks. In this regard, NSF hosted a conference/workshop in the late 1990s in which multiple examples of undergraduate programs of several examples of undergraduate curricula which included courses in the cognate sciences and in the ocean, atmospheric and hydrologic, and earth system sciences, were presented. NC State University presented an overview of cognate and atmospheric and oceanic sciences, which could result in double undergraduate degrees; such as a BS in Chemistry and also one in Chemical Oceanography or Marine Chemistry, and so on. It was quite popular at the NSF workshop, deeply discussed, and with the NSF blank of approval, subsequently adopted by several universities, such as at NCSU between the departments of Physics, Chemistry, Zoology[4], all with Marine, Earth & Atmospheric Sciences. This was a curricular revelation. Prestigious universities such as the Massachusetts Institute of Technology (MIT), the University of Delaware (UDE), the Naval Postgraduate School (NPGS) offer undergraduate and graduate courses in operational forecasting and communication, in both air and water. Additionally, the Marine Technology Society hosted a Conference and a comprehensive series of peer reviewed publications in 2006/07 that was chock full of R2O challenges and O2R solutions with real-time forecasting guidance, collectively called Stemming the Tide of Coastal Disasters (Fair Weather: Effective Partnership in Weather and Climate Services, 2003; Pietrafesa et al., 2006; Pietrafesa et al., 2007), but the recommendations were never funded by NOAA; save for the Legacy Earmarks existent at the time and still today.

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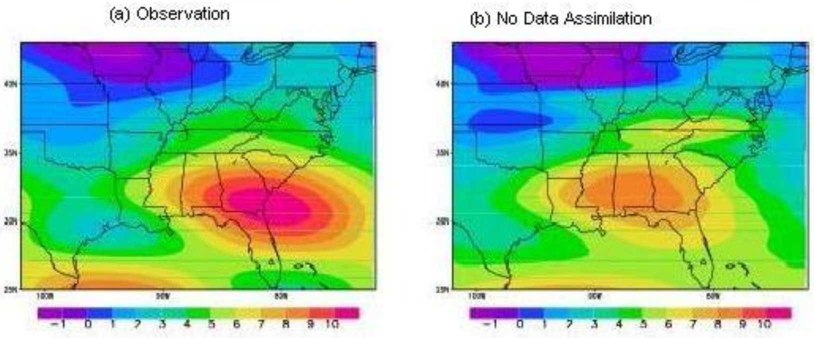
[4] https://meas.sciences.ncsu.edu/undergraduate/programs/marine-science/


(a) Observation

(b) No Data Assimilation

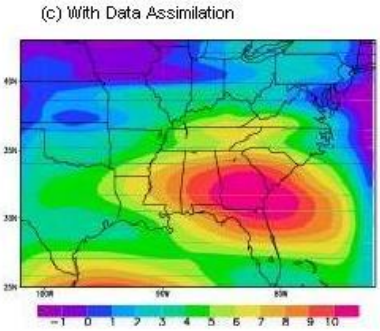

(c) With Data Assimilation

Figure 22. (a) NOAA observations; (b) the Caro-COOPS model output with no data assimilated; (c) the Caro-COOPS model output with data assimilated.

It is of note that the NOAA Office of Oceanic & Atmospheric Research (OAR) has been the go-to line office for development of research that conforms to the needs of the NWS. Moreover, all of the original twenty NOAA Cooperative Institutes (CI's), were all lodged in OAR. However in 2022, a new cooperative institute, CIROH, was spawned within the NWS.

CIROH

In 2022, the NOAA NWS Cooperative Institute for Research to Operations in Hydrology (CIROH) was created at the University of Alabama in Tuscaloosa.[5] Its mission was to conduct the research necessary to operationally forecast hydrology for the NWS and thus for the U.S. Following a call for proposals, there were 28 original universities and organizations that were selected to receive three years of funding to drive the CIROH mission. CCU was one of those 28. CCU has recently developed new QA/QC methodologies to evaluate data streaming via coastal piers, buoys and satellite sensors. CCU is also taking advantage of new statistical experimental prototype predictions of state variables developed in CIROH that will produce new services to be provided via the Internet. CCU scientists have also developed a new methodology to focus on processes of importance to regional super-regional stakeholders, to determine where and what kinds of new observing systems are needed in order to establish the essential observing backbone needed by NOAA to better meet its mission. Finally, CCU's initial overarching challenge is to connect the NOAA National Water Model, which is entirely land-based, to large bodies of water, such as the Atlantic and Pacific Ocean Basins, the Gulf of Mexico, and the Great Lakes. This is a proper role for a university partner. CIROH is really the first NOAA CI that is chartered to conduct operational forecasts of oceanic and large water body physics, and by extension, biological, geological and chemical state variables.

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[5] https://ciroh.ua.edu/

NEW TECHNOLOGIES

While Eulerian in-situ oceanic and Great Lake in-situ NOAA Marine Data Buoys and academic endeavors, such as the NOAA Caro-COOPS program described above, were laudable advances in real-time data acquisition to be utilized in operational forecasting, modern data gathering systems have advanced the state of the technology literally to unchartered waters and the atmosphere.

Uncrewed aerial (UAV's) and undersea (AUV's) vehicles, also known as drones, are vehicles without any onboard human pilots, crews or passengers. UAVs and AUV's were originally developed through the 20th Century for military missions too dull, too dirty or too dangerous for humans, and by the 21st Century, they had become essential assets to most militaries. As control technologies improved and costs fell, their use expanded to many non-military applications. Also, UAVs are acknowledged for their applications in modern cellular networks (5G). Over the past few decades, the number of mobile users has increased rapidly, not only the user count but also the user demands changed. As we moved from 1G to 5G, the very purpose of cellular communication networks took a turn from mere calling to a substitute for desktops, laptops, and other processing gadgets. Network operators had to deploy a large number of base stations (BSs) to serve user equipment with varying demands. To serve each user, a channel has to be allocated and if the user density goes beyond the available channels, the users would not be properly served resulting in low quality of service. Consequently, to improve the service, the operators are forced to install more BSs. For the deployment of terrestrial BSs, land needs to be acquired so it is a costly affair. UAV BSs are generally termed as aerial base stations (ABs or AirBSs), which are cost efficient compared to the expense of maintaining a terrestrial base station, and because of their inherent characteristics, namely, mobility, higher level of probability for line-of-sight signals, flexibility, and the easiness in changing the altitude level (adaptive altitude), UAVs constitute an inevitable element for the developments in search and rescue operations, vehicle-to-vehicle communication, load balancing in cellular networks, and so on. AirBSs are battery powered; however, their performance varies based on the altitude at which UAVs are placed and on the type of UAV. UAVs can operate as network relay nodes, as cellular-connected UAVs, as wireless networks, in maritime communication networks, with applications in weather forecasting, and disaster area photography to assist search and rescue operations, so have applications to the NOAA NWS, the NOAA Corps, the U.S. Coast Guard, and the U.S. Navy.

Atmospheric drones have been developed by the NOAA AOML (Cione et al, 2020) and used for the observations within and monitoring of dangerous and unpredictable conditions in atmospheric storms. As these devices are relatively inexpensive, compared to a manned aircraft, they can be sent into tornadoes and hurricanes so that specialists and weather forecasters got some new insights into the behavior of weather. Sensors used in drones are helping to provide new insights and details into storm fluid and thermodynamics (reference). These real-time operational data collection and transmission processes have resulted into the NOAA Team having been recognized as Gold Medal recipients in 2023 for their considerable advances in unmanned vehicle (Automated Atmospheric Vehicles and Automated Undersea Vehicles, AAVs and AUVs, respectively) reconnaissance in hurricanes and other severe storms (de Boer et al., 2019; Aksoy et al., 2017; Goni et al., 2017; Cione et al., 2020).

In the last 15 years, AAVs and AUVs have rapidly emerged as a vital tool for atmospheric and marine geoscientists, especially those involved in seafloor mapping and monitoring, in the cases of the latter. The ability of these vehicles to fly at relatively low altitude over the seabed enables them to collect spatial data at far higher resolution than surface vessels, especially in deep water. When used in conjunction with other platforms as part of a nested survey, a complete package of regional vessel-based mapping, high-resolution targeted AUV survey, and ROV video ground-truthing and sampling can be deployed. In addition to seafloor mapping, AUVs have been used to detect expelled hydrothermal or cold seep fluids in the water column. Continued development of new vehicles and sensors will increase the range of marine geoscience applications, while advances in artificial intelligence will increase reliability and flexibility. AUVs are already capable of making decisions that allow them to avoid seafloor or under-ice collisions, and increasingly these vehicles are developed with sufficient intelligence that they can adapt their surveys according to changes in the environment they are monitoring. When combined with new drivers such as Marine Protected Area monitoring and site surveys for offshore renewable installations, it is clear that AUVs will continue to play an increasingly important role in the exploration and monitoring of the oceans.

The NOAA National Mesonet Program (NMP) was created as a “Data Buy " program to support and ensure a weather-ready nation. The National Mesonet is a multi-functional, multi-faceted observational weather network of networks that delivers critical information required for improved weather prediction and warnings across the U.S. NOAA is funded by the U.S. Congress to buy real-time data from non-federal asset sources. As such, CCU and Florida Atlantic University (FAU) have created the South-East-Atlantic Ecological Network (SEA ECO-Net) of real-time reporting and data transmission land based observation stations (Goni et al., 2017; Klingman & Hallstrom, 2014; Yang et al., 2014; Esswein et al., 2012; Eidson et al., 2010) in SC, GA and FL. FAU has created a cloud based data transmission capability (Figures 23, 24, 25) that works on land and at sea. CCU and FAU have proposed to integrate in-situ observing networks and flux products which quantify exchanges between the offshore ocean through the coastal ocean and its inner continental shelf, the local to regional atmosphere, adjacent land and vegetation and connecting waterways, which are needed for improving diagnostic and prognostic numerical models, understanding near coastal domain dynamics, assessing the interactive coupling of the entire system, assessing coupled models and investigating the coastal zone’s role in climate. Integrated in-situ observing networks and flux products which quantify exchanges between the offshore ocean through the coastal ocean and its inner continental shelf, the local to regional atmosphere, adjacent land and vegetation and connecting waterways are needed for improving diagnostic and prognostic numerical models, understanding near coastal domain dynamics, assessing the interactive coupling of the entire system, particularly for CCU’s role in NOAA’s CIROH program.

CCU and FAU are also expanding the MESO U.S. concept by having created a Smart Reef offshore/nearshore program that is working to collect and transmit data in real time. They are proposing to deploy new experimental data sensors to measure and send nearshore oceanic state variable data in real time to the NWS, as a part of MESO U.S. for improved operational forecasting of weather in coastal nearshore waters off SC as a Test-Bed. The Sofar Inc. company is also engaged in this initiative because if the Smart Reef concept was implemented as a core component of MESO U.S., along with Fishing Pier observing systems, this could revolutionize weather forecasting in the coastal zones of the U.S. Instead of large bulky offshore buoys (cf. Figure 2a), which require large, costly vessels to deploy and service, advanced relatively inexpensive Sofar Ocean Inc. Spotter sensor systems (cf. Figure 25)[6] can be deployed, easily serviced by smaller craft and can be coupled with Fishing Pier stations (Figure 2b) to create the enabling capacity for truly operational coastal weather (air and sea) forecasting. The large bulky moorings have generally required costly near real-time data retrieval systems, such as the U.S. Department of Defense Iridium Satellite Network, while the Smart Reef systems utilize low cost FAU Mote Stack data transmission technology (Figure 23). This initiative offers the realization of coupling academia to industry to meet the needs of an operational federal agency, the NOAA NWS; the three-legged stool called for in the U.S. National Academy of Sciences Fair Weather, Effective Partnership in Weather and Climate

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[6] https://www.sofarocean.com/

Services Report of 2003, and could finally establish the basis for addressing that burning question of 1944 of when to launch the D-Day Campaign.

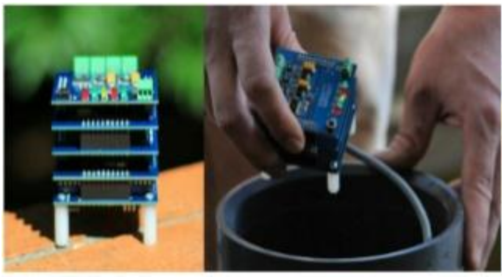

Figure 23. FAU Real Time High Capacity Transmission Waties Island SC

Figure 24. CCU Smart Reef offshore Waties Island SC

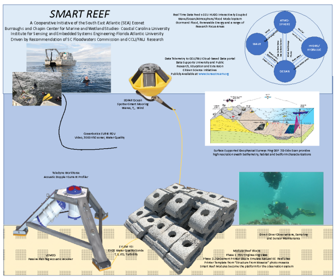

Figure 25. Smart Reef Real-time Sofar proposed deployment (see text)

CONCLUSIONS

The technological and scientific advances made as a part of the onset and emergence of a regional COOS that could be transitioned into a COOP are needed. However, the costs of maintaining and building out a COOP are very high; including mooring equipment, mooring platforms and supplies, personnel, and ship time. Thus, the essential back-bone observing array design, from national to regional scales, must be based on known, documented fundamental atmospheric and coastal oceanic phenomena and property distributions and an assessment of where foundational gaps exist in the essential backbone.

The proposed build-out of the NOAA IOOS observing network is presented above in the context of: 1) observing the state variables underlying the environmental processes known to be fundamental to coastal regions; 2) advancing the present state of knowledge of individual coastal systems; 3) advancing the prediction capabilities of coastal processes; 4) advancing the capability of the prediction of impacts of coastal processes on the environment and society of the coastal regions; 5) melding the needs of addressing high frequency, hour to day to week weather scale events, with the requirements of longer period monthly to seasonal to sub-seasonal to interannual to decadal time scales and differential nesting; 6) conducting quality assessment of data on the fly; and most importantly 7) making the case for the backbone build-out of an operational forecast system.

A fixed percentage of NOAA IOOS assets should be set aside for expansion of IOOS arrays if the collective array was to attempt to achieve national backbone status. If 25% of the IOOS budget were used for observing system equipment then at the nominal cost of a basic system, with both atmospheric and ocean state variable sensors, and with complete back-up could result in an 80% increase in the existing national coastal observing network equipment assets in one year alone. Outrageous but true! Instead of allowing the IOOS legacy earmarked targeted institutions to build up and build out their institutional infrastructure, the U.S. Congressional ear-markers and the federal agencies, specifically NOAA, should demand that a minimum of these limited dollars be spent in the building out of the essential national coastal observing backbone.

Finally, NSF should have a key role to play in the advancement of the science of oceanic to coastal ocean operational forecasting, as coastal and inland communities have an important need to know, in real-time, of impending hazardous storm events. These events are becoming more hazardous as climate change marches forward and at-risk coastal and inland communities need to brace themselves for the future and to build resilience. This requires cross-cutting research in the atmospheric, oceanic and socio-economic sciences. However, NSF program managers in the ocean and marine sciences are of the data collection ilk and have no formal training in the arena of operational forecasting, so are clueless to supporting the research necessary for OSE's and OSSE's in the coastal and nearshore ocean. That is a left-over legacy of decisions made by the ocean sciences community after WWII. It exists and persists today.

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