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NWS Office(s): WFO Wakefield, Meteorological Development Laboratory (MDL)

Name of NWS Researcher Preparing Report: John Billet

Partners or Cooperative Project: Cooperative

Project Title: A Storm Tide Observation, Analysis and Forecast System for
NWLON Water Level Stations in Coastal Oceans and Estuaries

UCAR Award No.: S09-75797

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SECTION 1: PROJECT OBJECTIVES AND ACCOMPLISHMENTS

1.1 Summary of Overall Project Objectives:

The goal in the first year of this project was to develop and test the VIMS *Real-time Storm Tide Observation & Forecast System* (*Rstofs*) and to demonstrate its ability to generate effective water level forecasts as guidance in near-real time for the benefit of NWS forecasters and emergency managers. The overall project objective is not to establish a permanent operational system in any one region of the country but to operate a prototype system in the lower Chesapeake Bay region for a period of one or more years to evaluate its performance as a potential operational system for the future.

Accomplishments: We have met the first year goal of developing and testing a prototype storm tide forecast system with a 36-hour projection period. *Rstofs version 2* is now operating in test mode at eight active water level stations in lower Chesapeake Bay and its output is available online to authorized users. After initial testing, *Rstofs version 1* was placed in operation shortly before the onset of the extratropical storm of 12-13 November, a storm which caused significant flooding in the Hampton Roads area. As web site access was not yet available at this time, storm tide graphics were sent to WFO Wakefield via email as the storm progressed. The system remained operational throughout and no data were lost. Thus recorded water level observations were compared with actual forecasts in real time in addition to comparisons made using historical data. One result of this experience was an update of *Rstofs* to *version2* (see Section 1.3). Underscoring the overall significance of extratropical storms in the lower Chesapeake Bay region, the NOAA National Water Level Observation Network (NWLON) station at Money Point, VA, recorded a high water height of 8.58 feet above MLLW at 7:12 pm on November 12, 2009. The maximum high water height recorded at Money Point during hurricane Isabel on September 18, 2003, was 8.34 feet above MLLW.

WFO Wakefield has taken advantage of the prototype website to use in its operational forecasts. The forecasters use the tidal forecasts produced as a guidance source which goes into making the final product which is then conveyed to NWS customers. With a number of nor'easters affecting the mid Atlantic this past winter the additional forecast guidance was very useful in improving real-time forecasts of tidal departures. In particular the adding of extra stations not in the MDL extra tropical storm surge product provided valuable additional information. The seminar provided by Dr. Boon contributed to forecaster understanding of how to use the product.

1.2 Scientific accomplishments:

A key component of the VIMS storm tide forecast system has been a proposed new *sea level anomaly* - a metric accounting for water level change that occurs at frequencies lower than *tidal* and *sub-tidal* oscillations. NOAA/NWS presently use an anomaly found as a running five-day average that brings water level observations into agreement with tide and surge predictions over the same 5-day interval[1]. Our definition of the sea level anomaly is the m30-MSL difference at any time t where m30 is the running mean of the last thirty days of six-minute water level observations recorded at a tide station and MSL is the tidal datum of mean sea level at that station as determined by NOAA/NOS for the current National Tidal Datum Epoch (1983-2001). Thus, it is essentially a running comparison of a short-term average (monthly mean sea level) with a long-term average (epochal mean sea level). Low-frequency sea level change in concert with long-term sea level trends is an active area of research among ocean scientists at the present time but on the practical side, our aim has been to utilize m30-MSL as an index of low-frequency change that can be directly observed on any given day, providing users of daily tide information an indication whether the present water levels on which these tides are propagating are elevated or suppressed, and by how much in either case.

Another event occurred in 2009 underscoring the importance of the sea level anomaly. Elevated water levels up to 2 feet above predicted occurred during a peak period in June 2009 along the greater part of the U.S. east coast. This anomaly was widely noticed among the public and the media, resulting in a special warning being issued by NOAA/NOS Center for Operational Oceanographic Products and Services (CO-OPS). Open-ocean processes along with unusual northeast winds were identified as the probable cause in a special CO-OPS report[2]. In addition to stressing the apparent need for anomaly warnings, for the U.S. east coast region in particular, we have shown that the same anomaly, m30-MSL, works well in our method for forecasting storm tides. Specific information on this topic is presented in the following section.

1.3 Operational forecasting accomplishments:

Shortly after the initial meeting of COMET project partners on July 7, 2009 (see Section 2), *Rstofs version1* was created for test and evaluation through the summer and early fall of 2009. Our evaluations included verification procedures following those done

[1] Extratropical Water Level Forecast at http://www.weather.gov/mdl/etsurge/.
[2] NOAA Technical Report NOS CO-OPS 051 available at http://www.tidesandcurrents.noaa.gov/.

previously by Arthur Taylor and others for the present MDL extratropical water level forecast at http://www.weather.gov/mdl/etsurge/. Along with this information, Mr. Taylor kindly provided a comprehensive set of historical storm surge forecasts that we have used for *Rstofs* verification as described previously in our 6-months COMET Cooperative Project report.

Rstofs version2 was implemented after noting certain features (e.g., low water diurnal inequalities) in 36-hour projections of the astronomic tide derived through time-local harmonic analysis of a moving 30-day series did not fully agree with the same features seen later as the projections were realized. The rationale for using repetitive (time-local) harmonic analysis was that it accounts for maximum water level variance at tidal frequencies in the least-squares sense, although we knew that 'time-local' analysis could not be used for tidal predictions extending more than a few days into the future. After seeing evidence that small discrepancies could appear even within a 36-hour projection period, we returned to standard harmonic analysis of 369-day records to obtain tidal harmonic constants for six NOAA NWLON stations and 279-day records to derive tidal constants for two VIMS stations. These tidal constants, not including the solar annual (Sa) and solar semiannual (Ssa) constituents, were used to generate the astronomic tide predictions used in *Rstofs version 2*. In addition to the MSL-MLLW offset customarily used to generate tide predictions relative to the U.S. chart datum (MLLW), we apply a further offset equal to the sea level anomaly, m30-MSL, as shown in Fig. 1.

$$\mathrm{Tide}_{\mathrm{MSL}} = \mathrm{h}_0 + \sum_{i=1}^{N} f_i H_i \cos(\omega_i t - \phi_i)$$

$$\mathrm{Tide}_{\mathrm{m30}} = \mathrm{Tide}_{\mathrm{MSL}} + (\mathrm{m30} - \mathrm{MSL})$$

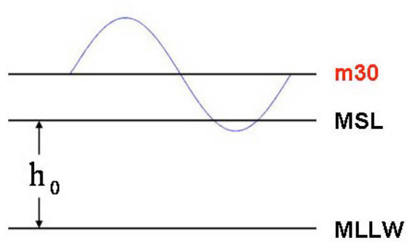

Figure 1. Schematic drawing showing predicted astronomic tide referenced to m30 ($\mathrm{Tide}_{\mathrm{m30}}$).

SECTION 2: SUMMARY OF RESEARCH AND EDUCATIONAL EXCHANGES

An initial meeting was held on July 7, 2009 at the Virginia Institute of Marine Science to address operational forecasting goals. John Brubaker, David Forrest and John Boon from VIMS met with John Billet from the Wakefield Weather Forecast Office and Arthur

Taylor from the NWS Meteorological Development Laboratory. This seminal meeting not only introduced participants from the different organizations who had not met in person before but also provided an important opportunity for the VIMS researchers to gain valuable insight into NWS forecast operations, forecast guidance procedures and forecast error assessment methods. A key benefit was an introduction by Mr. Taylor to the GRIB2 Decoder for the National Digital Forecast Database (NDFD), an essential resource enabling VIMS to have continuous online access to extratropical storm tide forecasts generated by MDL at selected grid points within the Chesapeake Bay region. As described in our COMET proposal, we use the MDL storm surge forecast to extend the 'measured' surge found as the residual (observed minus predicted) water level, adding it to the projected astronomic tide to obtain the forecast water level.

Forecasters were given some instruction about the *Rstofs* product and how it was derived in a presentation by John Boon at a workshop held at Wakefield in early December 2009. This has allowed the forecasters to begin looking at the product as several nor'easters affected the mid-Atlantic this winter. The feedback from the forecasters was passed back to VIMS researchers during a meeting at VIMS this spring. One of the comments was improving the web display by providing side-by-side comparisons of the *Rstofs* and extratropical storm surge guidance. This improved website offered the forecasters an immediate comparison of guidance. This could be used with the faster updating *Rstofs* product to track potential changes to tidal forecasts. As future events develop this coming year the forecasters will continue to provide real-time observational feedback on how the *Rstofs* product handles various weather situations.

In mid-June 2010, VIMS researchers Boon, Forrest and Brubaker met at NOAA offices in Silver Spring with Will Shaffer, Amy Haase and Ann Kramer from MDL's Evaluation Branch. Discussion focused on year-one activity and status of our COMET project and on comparison of some aspects of the forecast methodologies used currently by VIMS and MDL. Further work at MDL on verification and evaluation of ET surge was provided to the VIMS group. During the same visit, a VIMS presentation on *Rstofs* to a larger group of National Weather Service and National Ocean Service personnel generated an active and useful exchange of comments and ideas.

In mid-July 2010, COMET partners Brubaker and Forrest from VIMS and Billet from NWS met at WFO Wakefield for project updates and in order for the VIMS team to meet Jesse Feyen and Doug Levin, who were visiting the Wakefield office in connection with their development of NOAA's storm surge roadmap. COMET partners led an informal presentation/discussion summarizing the project's forecast system (*Rstofs*) development.

A common theme through the various exchanges was interest in issues of verification, the concept of water level anomaly and comparison of the approach used in *Rstofs* and MDL's etsurge. A summary of some aspects of these topics follows.

2.1 Verification of Storm Tide Forecast, Methods

The MDL 'etsurge' website has long provided reliable, computer-generated forecast guidance specifically designed for users exposed to flood risk and coastal hazards during extratropical storm events. The site is unique in providing forecast guidance updated at hourly intervals. A short update interval is important due to sudden changes in wind speed and direction occurring during these events. Other online sites provide water level information that is updated only every six hours and is designed for navigational safety guidance primarily.

Our research has focused on possible improvements and certain complementary features that can be realized through an alternate approach to the MDL forecast method. However, the foremost consideration in the evaluation of an alternate approach to storm tide forecasting is forecast accuracy. This must be established through rigorous verification procedures.

MDL Method - The primary difference between the MDL method and the one we advocate lies in the definition of the 'anomaly' term. The MDL anomaly at time *t* is expressed by a simple equation:

$$\text{Anomaly} = \text{Observation} - (\text{Tide} + \text{Surge}) \tag{1}$$

Averaging the terms in Eq. 1 over the 5 days prior to time *t* yields

$$\langle\text{Anomaly}\rangle = \langle\text{Observation}\rangle - \langle\text{Tide}\rangle - \langle\text{Surge}\rangle \tag{2}$$

where the angle brackets denote time averaging. A water level forecast for the next 4 days is then made using

$$\text{Forecast} = \langle\text{Anomaly}\rangle + \text{Tide} + \text{Surge} \tag{3}$$

The anomaly expressed in Eqs.1-2 is seen to be a correction term that brings observations into agreement with model predictions averaged over a 5-day interval. Model prediction errors in <Tide> and <Surge> in Eq. 2 are taken up by the <Anomaly> term so as to add the needed correction to the forecast in Eq. 3.

VIMS Method - The VIMS *Rstofs* system, as noted previously, defines a *sea level anomaly* as m30-MSL which is a measure of low-frequency water level change due to ongoing geophysical processes. Eq. 4 results after inserting m30-MSL in place of MDL's <Anomaly> term in Eq. 3, using subscripts to indicate the change in tide reference.

$$\begin{aligned} \text{Forecast} &= (\text{m30-MSL}) + \text{Tide}_{MSL} + \text{Surge} \\ &= \text{Tide}_{m30} + \text{Surge} \end{aligned} \tag{4}$$

$Tide_{m30}$ in Eq. 4 is a 'dynamic' tide that oscillates about m30, an elevation derived as a running 30-day mean updated half-hourly. Using the past thirty days as a 'window' on recent water level behavior, Eq. 4 becomes

$$\langle Observation\rangle - \langle Tide_{m30}\rangle = \langle Surge\rangle = 0 \qquad (5)$$

since both terms on the left have the same 30-day average. Thus 'Surge' in this window is simply the residual between observed and predicted water level. A zero-average residual, moreover, is consistent with the notion of meteorologically-induced storm surge as a short-term transient phenomenon that does not produce a net rise or fall over time.

Regarding the residual as *measured storm surge*, we look for a means of extending it 36-hours into the future and find it in the MDL forecast surge. Adding the projected surge to the projected $Tide_{m30}$, a 36-hour total water level projection results. But, unlike the MDL method, our approach has no correction factor bringing observations into agreement with predictions prior to the forecast. We can apply an offset to match measured surge with predicted surge at the time of the last observation but we are still left with the key question of forecast surge accuracy. To resolve the problem, we apply a *gain factor* to each MDL surge forecast prior to applying an offset matching it to the measured surge as shown in Fig. 2.

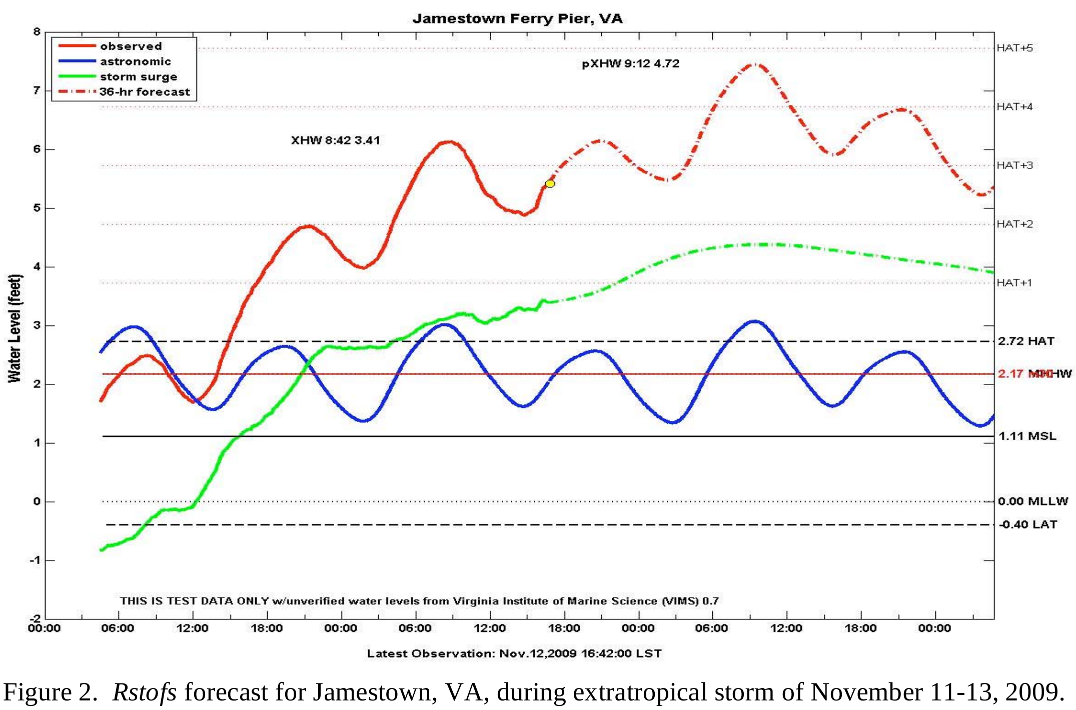

Figure 2. *Rstofs* forecast for Jamestown, VA, during extratropical storm of November 11-13, 2009.

Subsequent tests with historical data suggest that forecast surge amplitudes are too high and the gain factor required is approximately 0.7. Figures 3 and 4 below demonstrate the differences in observed and projected high water height using gain factors of 1.0 (GF10) and 0.7 (GF7), respectively.

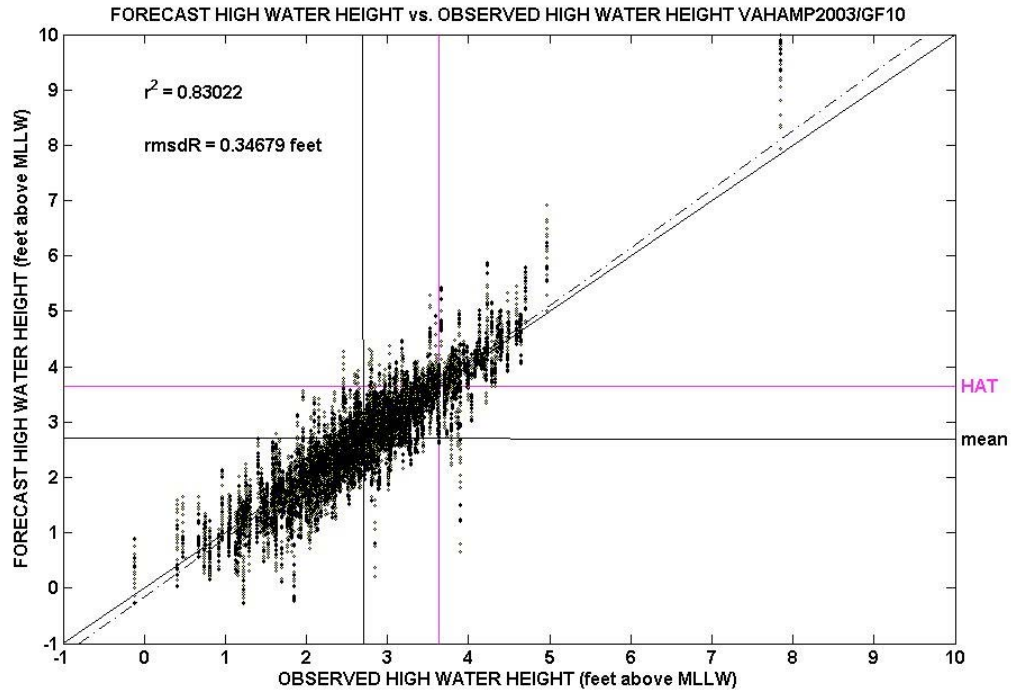

Figure 3. Forecast and observed high water comparisons for 2003, Hampton Roads (Sewells Point) VA. Root-mean-square deviation from regression is 0.35 feet, GF10.

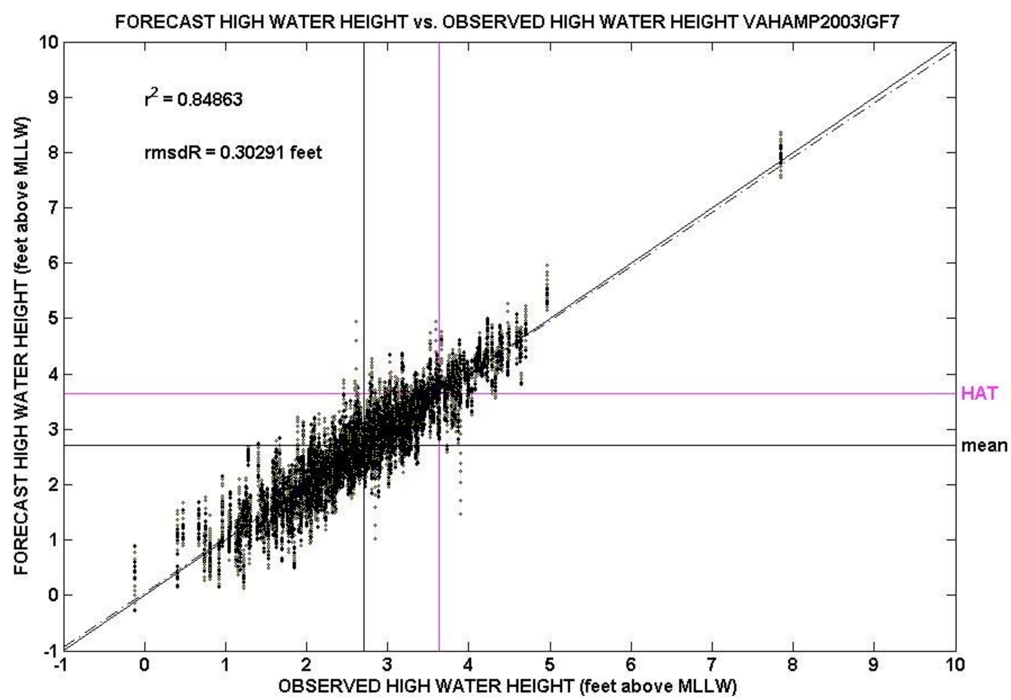

Figure 4. Forecast and observed high water comparisons for 2003, Hampton Roads (Sewells Point) VA. Root-mean-square deviation from regression is 0.30 feet, GF7.

The maximum high water height observed during hurricane Isabel on September 18, 2003, was slightly less than 8 feet above MLLW as shown in Figs. 3-4. It was obvious from a later comparison of measured and forecast surge that the forecast for this event was too high, a fact which led us to consider a gain factor correction. More detailed analysis resulting in graphs similar to Figs. 3-4 indicated that other high water forecasts were similarly affected, resulting not only in loss of accuracy but in greater spread among forecasts made at different times for the particular high water later observed.

SECTION 3: PRESENTATIONS AND PUBLICATIONS

Boon, J.D., J.M. Brubaker and D.R. Forrest. “Understanding Storm Tides”. Presentation at *Middlesex County Emergency Management Workshop, Deltaville, VA*, sponsored by Virginia Sea Grant Outreach Program, July 2009.

Boon, J.D., J.M. Brubaker and D.R. Forrest. “Storm Tide Forecast Evaluation: VIMS Observation-Analysis-Forecast System (OAFS)”. Presentation at *WFO Wakefield Winter Weather Workshop*, November 2009.

Brubaker, J.M. “Coming Soon – A Storm Tide Operational Forecast System at Jamestown”. Presentation at *Sea Level Rise Forum* sponsored by the James City County Concerned Citizens (J4C), James City, VA, December 1, 2009.

Brubaker, J.M. “Storm-related Observing: Development of a Storm Tide Forecasting System”. Presentation at VIMS/CBNERRVA Workshop entitled *Using Observing systems to Address Coastal Management Issues*, sponsored by the Chesapeake Bay National Estuarine Research Reserve in Virginia, January 27, 2010.

Boon, J.D. "Low Frequency Sea Level Change in Chesapeake Bay". Presentation at VIMS/CBNERRVA Workshop entitled *Using Observing systems to Address Coastal Management Issues*, sponsored by the Chesapeake Bay National Estuarine Research Reserve in Virginia, January 27, 2010.

Brubaker, J.M. and J.D. Boon. "Modes of Subtidal Variability of Surface Elevation and Exchange in Chesapeake Bay". Presentation at AGU Ocean Sciences Meeting in Portland, Oregon, February 22-26, 2010.

Boon, J.D., J.M. Brubaker, D.R. Forrest. “Storm Tide Observation, Analysis and Forecast System for Lower Chesapeake Bay”. Presentation at Chesapeake Modeling Symposium, special session entitled *Exceptional Atmospheric and Hydrodynamic Processes and Events: Observations, Models, Forecasts, Response and Communication***.** Annapolis, MD, May 11, 2010.

Boon, J.D. "Sea Level rise and the Impact of Lesser Storms". Workshop on *Sea Level Rise and Coastal Infrastructure: Predictions, Risks and Solutions* sponsored by the University of Maryland and the American Society of Civil Engineers, Reston VA, June

9-10, 2010. Invited paper submitted for publication in ASCE Monograph (B.M. Ayyub, M. Kearney eds).

Boon, J.D., J.M. Brubaker, D.R. Forrest. "Real Time Storm Tide Observation & Forecast System". Presentation at NOAA/NWS MDL office in Silver Spring, MD; Joint office conference attended by MDL staff and NOAA/NOS CO-OPS staff, June 15, 2010.

SECTION 4: SUMMARY OF BENEFITS AND PROBLEMS ENCOUNTERED

4.1 VIMS:

On track for the midpoint of a two-year project, benefits at this stage are of an intermediate nature. A fully functional prototype version of an analysis and forecast system has been developed and implemented. Some testing methodologies have been developed and applied to sample events and periods at selected stations. Forecasters at Wakefield have been introduced to the system and have provided initial feedback. The work of year one has provided the foundation and framework for the comprehensive evaluation and verification work of year two that is needed in order to validate applicability of the forecast approach to a range of storm types and conditions and to other U.S. coastal regions. The early feedback from forecasters is a crucial benefit in designing appropriate and effective forecaster training in year two.

No special problems have been encountered during the first year of study. We have received excellent cooperation and assistance from our partners at Wakefield WFO as well as our partners at MDL in Silver Spring. It has been a pleasure working with both groups. We are also pleased at the interest shown by NOAA/NOS personnel at the Center for Operational Oceanographic Products and Services in Silver Spring, MD.

4.2 WFO Wakefield:

Wakefield has set up the *Rstofs* website as part of the local marine and coastal flood wiki page. This page contains links to the presentations about this system as well as links to the forecast product. This has allowed the forecasters to begin using *Rstofs* for guidance when issuing products for the locations where we receive data. Also since *Rstofs* produces forecasts for sites not normally provided by the extra tropical storm surge guidance product, these additional sites such as Windmill Point allow the local office to provide additional information to our customers.

SECTION 5: PLAN OF WORK FOR THE NEXT YEAR

Some specific parameters of the current implementation of the *Rstofs* forecast system, notably the gain factor of 0.7 applied to the MDL model forecast surge, were determined based on successful trials for the stations and time periods tested so far. VIMS and WFO Wakefield partners in this COMET project are in full agreement that an important activity in year two is to broaden the testing and parameter evaluation to include a range of weather and tide characteristics and additional stations. This additional verification work will help determine the applicability of the forecast system to various coastal regions and identify possible limitations or cautions that should be observed under certain storm conditions.

As proposed, forecaster training will be provided in year two. Development of effective training will be an iterative and interactive process. In the early stages, Wakefield forecasters will be co-developers and will provide feedback on how they can make the best use of the information given the time constraints and other practical considerations from the forecaster perspective. They will also identify topics and areas of focus to include in training materials that will be developed and provided by VIMS. For example, early feedback from forecasters at Wakefield has already indicated a need for further information on the anomaly used in *Rstofs*, and how it relates to the MDL anomaly. They have suggested that examples illustrating the differences would be helpful to them. We have begun to address the anomaly comparison, as noted in Section 2, and will continue with this and related activity in year two.

SECTION 6: FUNDING REQUEST

The amount of funding requested for year two is unchanged from the original proposal. However, we propose an internal adjustment in the budget for VIMS in year two, shifting $1,000 from travel to contractual services, to reflect a substantially greater level of participation by Dr. John Boon, VIMS professor emeritus. In fact, Dr. Boon has already spent far more time on the project than budgeted for year one, essentially increasing his cost-sharing donation of time for year one considerably (see Budget Explanation on the last page). Beyond the commitment of time, he brings a wealth of experience and expertise to this COMET project, and the project will continue to benefit from his participation in year two.

NWS Project Budget Page

YEAR 1

	COMET Funds	NWS Contributions (FY)
University Senior Personnel		
1. John Brubaker	**8,270.**	**NA**
2. David Forrest	**6,750.**	**NA**
Other University Personnel		
1.		**NA**
2.		**NA**
Fringe Benefits on University Personnel	**6,008.**	
Total Salaries + Fringe Benefits	**21,028.**	
Contractual services		
John Boon, VIMS Professor Emeritus	**1,250.**	
NWS Personnel		
1.	**NA**	250
2.	**NA**	100
Travel		
1. Research Trips	**2,000.**	1000
2. Conference Trips	**1,000.**	500
3. Other		
Total Travel	**3,000.**	1500
Other Direct Costs		
1. Materials & Supplies	**300.**	**NA**
2. Publication Costs	**(usually NA)**	1000
3. Other Data		
4. NWS Computers & Related Hardware	**NA**	
5. Other (specify)		
Total Other Direct Costs	**300.**	
Indirect Costs		
1. Indirect Cost Rate	**43%**	
2. Applied to which items?	**All items listed above.**	
Total Indirect Costs	**10,999.**	
Total Costs (Direct + Indirect)	**36,577.**	2500

NWS Project Budget Page

YEAR 2

	COMET Funds	NWS Contributions (FY)
University Senior Personnel		
1. John Brubaker	**8,684.**	**NA**
2. David Forrest	**7,088.**	**NA**
Other University Personnel		
1.		**NA**
2.		**NA**
Fringe Benefits on University Personnel	**6,309.**	
Total Salaries + Fringe Benefits	**22,081.**	
Contractual services		
John Boon, VIMS Professor Emeritus	**2,250.**	
NWS Personnel		
1.	**NA**	250
2.	**NA**	100
Travel		
1. Research Trips	**300.**	800
2. Conference Trips	**700.**	1000
3. Other (Education and outreach)	**1,000.**	200
Total Travel	**2,000.**	2000
Other Direct Costs		
1. Materials & Supplies	**300.**	**NA**
2. Publication Costs	**(usually NA)**	2000
3. Other Data		
4. NWS Computers & Related Hardware	**NA**	
5. Other (specify)		
Total Other Direct Costs	**300.**	2000
Indirect Costs		
1. Indirect Cost Rate	**43%**	
2. Applied to which items?	**All items listed above.**	
Total Indirect Costs	**11,451.**	
Total Costs (Direct + Indirect)	**38,082.**	4000

NWS Project Budget Page

Budget explanation

Salary: funding is requested for 1.2 months per year salary support for J. Brubaker and for D. Forrest. They will each contribute an additional 0.3 months per year as cost sharing (see below) for a total of 1.5 months effort per year to the project.

Contractual services: Funding for consulting services of J. Boon, VIMS Professor Emeritus is requested in the amount of $1,250 for 0.25 month in year one and $2,250 for 0.45 month in year two. He will contribute an additional one month of effort per year as cost sharing (see below) for a total of 1.25 months effort in year one and 1.45 months effort in year two to the project.

Travel: Trips to NWS offices in Wakefield, Virginia and Silver Spring, Maryland will facilitate collaboration between university and NWS personnel. We will also visit local emergency managers in different jurisdictions to learn how currently available forecasts are used and how enhanced water level forecasts can be made as useful to them as possible. Travel to appropriate conferences for presentation of results of this project would also be covered by the requested funding.

Supplies, copier: minimal supplies will be required, primarily for data storage and report preparation and distribution.

Indirect costs (Facilities & administrative): the current federally negotiated F&A rate is 43%.

Cost sharing summary: Salary, fringe benefits, and indirect costs for the contribution of 0.3 months for J. Brubaker and D. Forrest is valued at $7,518 in year one and $7,894 in year two. J. Boon, VIMS Professor Emeritus, will donate 1 month effort per year to the project. His equivalent earnings as a private consultant would be $5,000 for 1 month plus $2,000 for self-employment costs (total of $7,000 per year).