FINAL REPORT

Implementation of the Caribbean Regional Integrated Coastal Ocean Observing System (CariCOOS)

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1) Project Summary

The project proposed the initial implementation and operation of a coastal observing system capable of providing for stakeholders coastal information needs. Prioritary stakeholder needs identified through CaRA are real time data, products and forecasts for coastal weather, coastal waves, coastal currents, storm surge driven coastal inundation and water quality. In order to provide for these needs the program identified the following priority actions:

- Emplace and maintain a core of coastal observing assets that will provide near real time "in situ" observations of coastal circulation, waves, coastal weather, SST and salinity at representative and operation-relevant sites.
- Implement an operational modeling program that will generate coastal wind, wave and circulation forecasts while providing an integrative regional context to observational data from core coastal observing assets. The proposed modeling program will also generate improved storm surge driven coastal inundation maps and surface tidal elevation products. The core coastal observing system serves also to provide validation points for the forecast system being implemented.
- Develop, in collaboration with NOAA CoastWatch Caribbean/Gulf of Mexico Node colleagues and the ESA supported CoastColour program, regionally focused coastal water quality products, including sea surface temperature, turbidity and chlorophyll a concentration, derived from remotely sensed data and validated using in situ observations.
- Maximize usefulness and availability of the above data streams by implementing DMAC standards and procedures, assuring data availability to the IOOS community, to interested federal and state agencies (i.e. National Weather Service, and to the National Buoy Data Center, DRNA-PR, PR Emergency Management Agency, Puerto Rico Electrical Power Authority - PREPA). Assure usefulness to all stakeholder sectors by implementing tailored product design and delivery strategies in consultation with CaRA council and committees.
- Assure cost effective product delivery through model and imagery calibration with an optimum number of in situ assets thus minimizing infrastructure installation and maintenance; further optimization through the use of existing observational and modeling infrastructure, expertise and strategic partnering.

2) Accomplishments

Emplace and maintain a core of coastal observing assets

As an initial step towards the development of a responsive, flexible and robust observing system, The Caribbean Regional Association for Coastal Ocean Observing (CaRA), using a range of instruments and strategies, undertook a detailed survey of user needs for region coastal ocean data and data products targeting different sectors including government agencies and their environmental and emergency mangers, the marine transportation industry, and, of particular interest for the region, the tourism sector. CaRA further undertook an inventory of

existing assets in the region. This inventory, contrasted to explicitly identified user needs, served to identify existing observational capabilities and data gaps. Prioritary stakeholder needs identified through these means were real time data, products and forecasts for coastal weather, coastal waves, coastal currents, storm surge driven coastal inundation and water quality. To meet these needs while minimizing the expense and effort of maintaining a large array of observing assets, a strategy was implemented towards obtaining coastal ocean data representative of the prevalent marine regimes: Atlantic, Caribbean, Mona Passage and the USVI archipelago and towards filling coastal meteorological observation gaps throughout the region.

To address the need for coastal ocean data, CariCOOS subcontracted the University of Maine Physical Oceanography Group to emplace, operate, maintain and disseminate data from three coastal data buoys located strategically; one off the port of San Juan Atlantic waters, and two in Caribbean waters off the island of St. John and the port of Ponce. These buoys, equipped with redundant wind sensors, sensors for air and surface water temperature, surface salinity sensors, full water column acoustic Doppler current profilers and sensors for wave height and direction were duly deployed and currently serve data to the entire region. Additionally, given needs particular to the NW coast of Puerto Rico and Mona Passage, a DataWell WaveRider wave data buoy was emplaced off the point of Rincon on the West coast of PR. CDIP at Scripps Institution of Oceanography assists CariCOOS in the operation and data handling of this buoy. Maintenance of all buoys involves yearly removal from the mooring, transport to land for refurbishment, replacement and calibration of instruments, cleaning and painting and re-emplacement.

To fill gaps in regional coastal weather observation CariCOOS entered into an agreement with corporate subcontractor WeatherFlow Inc., which successfully emplaced a network of twelve coastal weather stations located around the island of Puerto Rico and at strategic sites in the US Virgin Islands. Through recurrent sub-awards, WeatherFlow maintains this equipment and supplies the data stream to CariCOOS and to the San Juan Weather Forecast Office (WFO) of the National Weather Service (NWS) through the MADIS system. Additionally, in order to further fill coastal winds observational gaps we upgraded two existing PR Seismic Network stations with at Mayaguez and Arecibo. Improvements to these stations involved replacement of the 20 ft anemometer mounting poles with hurricane-resistant 35 ft poles in order to minimize interference by adjacent structures. Finally CariCOOS emplaced a weather station at a municipal facility near the coast in Rincon, PR.

CariCOOS co-operates with the Center for Secure and Resilient Maritime Commerce (CSR), a DHS Center of Excellence, a HF Radar array for surface current mapping and vessel tracking. Rutgers' Coastal Ocean Observing Laboratory, a partner in the CSR project, provided one HFR system on loan and a second system was procured on loan from TAMU with the assistance of the IOOS HF Radar program office. Together these systems constitute the CariCOOS HFR array providing surface current data for the eastern portion of the Mona Passage. CariCOOS hosts data assembly and serves data from the array on its web page. This data is in turn remitted to the National HFR Network. As part of this cooperation, CariCOOS also hosts an AIS Mona Passage ship traffic monitoring system.

This initial phase of the CariCOOS observing system now provides a wealth of near realtime *in situ* observations of regional winds, coastal currents, nearshore waves, and coastal SST and salinity at representative sites relevant to stakeholder needs. For the region, these accomplishments represent a significant increase in ocean and coastal data.

Implement an operational modeling program

Waves

Prior to the commencement of the CariCOOS project, nearshore wave forecasts were frequently inaccurate given the complex bottom topography of the region and the coarse model grid resolution of Wave Watch 3 (WW3), the then available NWS operational model. To fill this gap, CariCOOS chose the SWAN wave model, a third-generation wave model that computes random, short-crested wind-generated waves in coastal regions and inland waters for which local expertise had been previously developed as a doctoral thesis.

Initially, model implementation at 1 kilometer resolution for the entire north Atlantic Basin domain proved to exceed existing computational capacity. Subsequently, model implementation was re-structured so as to nest SWAN within WW3 for which NOAA/NCEP data at boundaries set by 2 existing and 6 new virtual data nodes at sites to the north and south of the PR/USIV region. Initialization with these boundary conditions allowed for more agile implementation in the domain of interest.

Field-validated output of the new SWAN implementation for the CariCOOS domain at 1 kilometer resolution is routinely disseminated through our web interface (http://www.caricoos.org/drupal/swan_multigrid). This CariCOOS SWAN implementation has been adopted by NWS SJU WFO for wave forecasting and is published operationally at http://www.srh.noaa.gov/sju/?n=marine1_models. Additionally a 50 meter resolution product for assistance in forecasting hazardous beach conditions and support for port approach operations has also been implemented and validated and is available for selected sub regions.

Detailed model skill assessment was undertaken using data from existing CariCOOS buoys and short-term AWAC and pressure sensor deployments. Outcome for the CariCOOS SWAN implementation indicated significant improvement over the latest generation of WW3 for Puerto Rico. Detailed results were reported in:

Anselmi-Molina C. M. M. Canals, J. Morell, J. Gonzalez, J. Capella and A. Mercado. 2012. Development of an Operational Nearshore Wave Forecast System for Puerto Rico and the U.S. Virgin Islands. J. Coastal Res. 28 (5) 1049–1056.

Web-based products built from model output are operationally displayed in our web page, and in the local NWS page, and the model output grids are available through the CariCOOS THREDDS/OpenDAP server. The NWS model is run at their local HPC server while the CariCOOS model is run on HPC servers at Isla Magueyes.

Winds

Initially, at the request of San Juan NWS-WFO, CariCOOS proceeded with experimental implementation of the NCAR Weather Research and Forecasting model (WRF) at 4 km resolution. Output from this model implementation was made available to NWS and CariCOOS staff for early evaluation. Subsequently, the model was adopted, further developed and optimized by the San Juan NWS-WFO for operational implementation. A final report on validation of various wind forecast models (GFS, NAM and WRF) with reference to specific

CariCOOS site observations for the period of mid April, 2011 – July, 2011 was produced with favorable results for the WRF model.

Having entered into a mutual agreement (MOA) with San Juan NWS-WFO, among other duties, CariCOOS has agreed to duplicate operational runs of this model as a backup to the San Juan NWS-WFO implementation.

Coastal Inundation

The PR CZMP office contracted CariCOOS to develop a maximum of maximums inundation map for a category 2 hurricane, the most frequently observed in the region with the explicit purpose of using maximum of maximum (MOM) inundation elevation lines as one of a set of multiple criteria for the delineation of the maritime-terrestrial boundary for the Commonwealth of Puerto Rico. Coupled parallel versions of the ADCIRC circulation model and the SWAN spectral wave model, both using an existing FEMA unstructured finite element grid, are used to estimate the three setups that contribute to the overall storm surge: wind, pressure, and wave setup. The coupling between ADCIRC and unSWAN uses the University of Notre Dame's version (pADCSWAN). The resulting MOM map incorporates the output of 136 trajectory runs with hurricanes attacking the islands at 5 different track angles selected from hurricane climatology and along 24 - 31 track lines spaced apart at 10 nautical miles track to track.
The capability thus developed, including equipment and expertise, was leveraged for analogous implementation of Cat 5 and Tropical Storm MOM maps. These new maps, coupled to the Cat 2 MOM constituted a climatologically averaged catalog delivered to the PR State Emergency Management Office in printed and digital format (shapefile) at the CaRA 2011 General Assembly.

Currents

As part of its commitment to coastal stakeholders including fishermen, search and rescue operators and fisheries management officials, CariCOOS sought to provide operational, high resolution, coastal circulation model forecasts of coastal ocean currents. The CarICOOS implementation proposal incorporated a strategy to fulfill the need for these circulation products through three approaches. Progress towards each of these goals is related below.

1) *Maximizing the return from the coastal inundation component of the proposal by utilizing the ADCIRC model tidal and velocity fields*

Given the ability of ADCIRC to simulate sea surface elevations under normal-tidal and tropical cyclone conditions, and the massive computational resources necessary for implementation of baroclinic GCMs, CariCOOS explored the use of this model for coastal circulation.
Following extensive model development, a mature, high resolution, tidally driven ADCIRC model implementation for Puerto Rico was tested versus direct ADCP velocity time series at the three CariCOOS buoys and also versus harmonically reconstructed tidal currents at two NOAA NOS stations. The main findings are:

- Model speeds are consistently lower than direct observations and NOAA harmonic reconstructions at all locations considered in this study;
- ADCIRC model flow fields around PR and the USVI are currently inadequate for operationally sensitive search and rescue operations;
- Especially troublesome are the very small simulated flows near the major ports of San Juan and Ponce;
- The relative success of the model on the western PR shelf and around the US Virgin Islands suggests the model's shortcomings might not be intrinsic and there might still be room for improvement in the simulations through the tuning of model.

The CariCOOS ADCIRC model implementation scheme is currently being revised by colleagues at the U. Notre Dame.

2) A regional implementation of ROMS nested in HYCOM in collaboration with UM RSMAS

As set forth in rescoping letters, initially, implementation of this model was hampered by funding limitations which disallowed significant time commitments on the part of our RSMAS colleague. Nevertheless, advances in the last two years include:

- development of computational grids including a detailed bathymetry
- development a scheme for nesting ROMS in global HYCOM
- acquisition, set up and assignation of computational resources
- successful finalization of extensive hindcast series
- Implementation of satellite SST assimilation
- Implementation of NAM climatological forcing

In summary, a pre-operational system for the CariCOOS region is currently in place with daily numerical and graphical output and model output is being archived. Assimilation schemes for in situ ADCP currents and salinity are currently being developed under the new project entitled "Advancing CariCOOS". Similarly, a continued skill assessment effort is underway.

3) Secure the output from the various community North Atlantic GCMs, explore their suitability to generate products to meet stakeholder needs.

The Center for Ocean-Atmospheric Prediction Studies (COAPS) at Florida State University has agreed to provide CaRA/CariCOOS with Global HyCOM model output for our region. The model output is being used in the above described regional implementation of ROMS nested in HYCOM in collaboration with UM RSMAS.
The Naval Oceanographic Office (NAVOCEANO) operational ocean prediction system for the Gulf of Mexico and Caribbean, AMSEAS, is based on the NRL-developed Navy Coastal Ocean Model (NCOM) with resolution of 1/36 degree (~3km) horizontal and 40

levels in the vertical. CariCOOS has evaluated output for our region of this model provided by the Northern Gulf Institute as part of IOOS-supported modeling testbed project. Initial validation of this model output using data from outer shelf bouys is highly favorable. AMSEAS model output is now in use providing boundary conditions for our high resolution ROMS harbor applications under "Advancing CariCOOS".

Additional GCM output evaluated included NCEP's RTOFS and that of NRL's Experimental Real-Time Intra-Americas Sea Nowcast/Forecast System (IASNFS).

Develop regionally focused coastal water quality products

Optical Properties

Estimation of suspended sediment loading and turbidity of coastal waters constitute high priorities in the CariCOOS region. Environmental managers require this data to assess and devise management strategies for minimizing threats to sensitive coastal ecosystems including coral reefs and sea-grasses while diver preference for clear waters, drives recreational needs. As satellite remote sensing constitutes and expedient and cost effective means to meet these stakeholder demands, CariCOOS adopted a strategy of developing a suite of field-validated remote sensing products.

Following authorization by the European GlobeColour program, project CariCOOS gained access to moderate resolution remote sensing ocean color data from both, the European Space Agency's ENVISAT carrying the MERIS instrument, and NASA's MODIS radiometer aboard TERRA and AQUA. Products depicting surface chlorophyll content and diffuse attenuation coefficients (Kd) have been served daily through the CariCOOS web page at 1000m resolution. High resolution imagery (300m) from the MERIS instrument has been also been made available to CariCOOS via partnership in ESA's CoastColour program ; the database extending from 2005 to 2009 will be available to the community via a CariCOOS ArcGIS and THREDDS servers.

CariCOOS also negotiated and obtained custom remote sensing imagery from the NOAA CoastWatch Caribbean node. In order to provide ground truth data for such imagery to be utilized for regional water quality monitoring, CariCOOS implements a weekly sampling program for chlorophyll *a,* total particulate carbon and seawater absorption at Guánica and La Parguera inshore stations. A suite of 3 C-Star beam transmissometers for the development of optical proxies for the above water quality parameters was purchased and is currently being deployed in our CTD package. Sampling at the Caribbean Time Series Station offshore reference station is performed aboard R/V SULTANA or ships of opportunity. Despite the demise of the ENVISAT platform the CariCOOS field sampling program continues to be implemented providing ground truth for MODIS imagery and the upcoming ENVISAT replacement.

Ocean Acidification

CariCOOS collaborates with NOAA's PMEL in the implementation of the NOAA Ocean Acidification Program. Complementary chemical, physical, and meteorological measurements monitored within the La Parguera Marine Reserve are used to track the dynamics and controls on local carbon chemistry. A moored autonomous pCO2 system (MapCO2) is deployed over the forereef of the Cayo Enrique shelf reef (17.95 N, -67.05 W) 1.6 km from the coast. Autonomous capability of the MapCO2 buoy provides continuous 3 hourly measurements of both air and dissolved CO2 mole fraction along with temperature, salinity, and dissolved oxygen. The data

are transmitted daily via Iridium satellite link for quality control at NOAA PMEL and are routinely merged with oceanographic and meteorological data when available from the nearby ICON/CREWS station. Autonomous instrumental observations are validated and supplemented on a weekly basis through laboratory analysis of discrete samples. Bi-weekly surface water samples are collected at the MapCO2 buoy and offshore. The offshore station (17.87 N, -67.02 W) is one mile from the shelf-edge at a depth of approximately 500 m. Profile measurements of chemical and physical parameters are continually taken using a SBE25® conductivity, temperature, and depth recorder (CTD). Seawater samples are collected using a Van Dorn type sampler bottle at approximately 3 m depth. The seawater samples are drawn from the sampler into 250 mL BOD flasks and stored at room temperature for analysis within 24 hours for total alkalinity, spectrophotometric pH and silicate and phosphate content where necessary for alkalinity computations.

Maximize usefulness and availability of the above data streams

Data Management and Communications (DMAC)

This 3-year CariCOOS funding cycle saw the creation and implementation of a CariCOOS DMAC infrastructure which has been built up to the present. IT personnel was hired and exposed to the wider IOOS DMAC community for training purposes. Server hardware and connectivity were acquired and deployed. The CariCOOS web portal was built and populated with products created from the ocean observing system, and from model data streams, and supplied to our stakeholders. The CariCOOS observing system, and the resulting data holdings, during this first cycle included 12 MESONET stations recording wind speed, direction and temperature at 5 minute intervals and two coastal metocean data buoys recording wind speed and direction, currents at 6 depths, wave height and direction, salinity and sea surface temperature reporting at 1 hour intervals. During this period, and after comprehensive consultation with regional stakeholders, CaRA/CariCOOS developed a 10 year buildout plan addressing high priority existing and foreseeable data and product needs for the region.

Recognizing an initial lack of local DMAC expertise, a core of services was subcontracted to UMaine and WeatherFlow. UMaine supplier of the CariCOOS coastal data buoys, provides the primary QA/QC on the buoy data, pushes the data stream to NDBC and packs and supplies these data in standard NetCDF format. WeatherFlow provides coverage of coastal winds around PR and the USVI through the 12 station MESONET and allows for the dissemination of these data through our portal services in csv text format and transfer of the data to NWS SJU WFO through the MADIS system.

While UMaine and NDBC provide access to buoy data through their own THREDDS, ERDAP and SOS DIF services, CariCOOS THREDDS services were improved allowing for data discovery as well as access to SWAN model output. All CariCOOS data, including MESONET data, are now posted to http://www.caricoos.org/drupal/es/data_download available to all stakeholders.

As data storage and web product development during early CariCOOS DMAC consisted of multiple data files scattered through our servers, steps were taken during this stage to merge and compile all product data in a MySQL database. Dedicated and redundant storage servers were acquired and configured in the redundant RAID 60 format.

Initially a provisional HPC center was established in facilities of the Department of Marine Sciences (DMS) at UPRM with a dedicated server rack and peripheral communications and

networking hardware and software. In 2010 this equipment was moved to the CariCOOS program office in at the DMS facilities on Magueyes Island in order to establish the CariCOOS node 1 High Performance Computing (HPC) Center. Subsequently, additional facilities were assigned to CariCOOS at the R&D Center of UPRM in Mayaguez. These facilities were refurbished with improvements to the power infrastructure, provisions for backup power, and environmental control. In 2011, CariCOOS initiated the buildup of a second HPC center at this facility. Coupled to the original facility on Magueyes Island, this development allows redundant model execution, data processing and storage and data product construction strengthening the capacity of CariCOOS to offer uninterrupted operational services. These facilities also allow CariCOOS to meet its commitments with the San Juan WFO for WRF and SWAN model mirroring. The current state of CariCOOS HPC capabilities is shown in the table below.

CariCOOS HPC Infrastructure

NAME	core processors #	Application
sandbox	**2**	utility/web page tests/mySQL DB
bluesteel	**2**	scripts/web page
modelo4 = marejada	**48**	coastal hazards inundation modeling
modelo3	**32**	SWAN model
modelo2	**32**	WRF model
manoa	**8**	Storage/CODAR/JOBANER/AMSEAS
corriente	**48**	HYCOM/ROMS model
swan	**48**	SWAN Clone
storage	**8**	storage
modelo1	**4**	OpenDAP/THREDDS data server
blue2	**2**	scripts/web page
NAS	**1**	storage

Web Products

The CariCOOS web page serves data products reporting buoy and MESONET data in the form of regional maps, graphs and tables developed in house. The web page also served regional experimental graphical map forecasts for waves (SWAN) and for regional winds (WRF) and a THREDDS/OpenDAP server for SWAN model output was implemented.

The CariCOOS web page is based on the DRUPAL platform. The web page front end presents a regional map depicting near-realtime data on winds, waves, currents and tides from CariCOOS and other assets operational in the region. This product also provides the data in tabular and graphical format and allows immediate comparison of data to forecasts. In the case of winds, observational data is contrasted to the NWS graphical forecast data. In the case of waves, CariCOOS buoy data is contrasted to SWAN output for that site.

Besides being made available as above and through the OpenDAP/THREDDS data server, model output is provided as animated maps. SWAN output maps show wave height, period and steepness. AMSEAS output maps depict currents, SST and sea surface salinity (SSS).
As a service to stakeholders, the CariCOOS page also mirrors data and products produced by partners and collaborators. Satellite imagery provided by GlobeColour depicting surface chlorophyll and diffuse attenuation is renewed daily. Surface current maps of the Mona Passage as produced from the CSR/CariCOOS HF Radar array by the NOAA HF Radar National Server and Architecture Project and Scripps CORDC, are made available in near realtime, as are the Coastal Marine Zone Forecasts of the NWS San Juan WFO. Web page use is routinely monitored using the Google Analytics tool. The page is currently averaging about 15,000 visits per month.

CariCOOS maintains an active outreach and education program targeting both formal and informal education. An important part of the E&O program is training middle school teachers and US Coast Guard Auxiliary instructors in the interpretation of environmental information in general and of CariCOOS web-based products in particular.

State of the Observing System

Prior funding for the establishment of CaRA, allowed for meaningful stakeholder engagement (sector meeting, interviews, and needs assessments) with numerous partners (NOAA CSC, Puerto Rico Sea Grant Program, CIEL, etc.) to objectively assess end-user needs. With this background, funding of our proposal for implementation of the observing system allowed us to build the basic infrastructure to collect and integrate the highest priority variables wind, waves, & currents critical for our tropical island regime. Since the Caribbean region did not benefit from the infrastructure investments like some of the other regions, our efforts required building the observing system from the bottom up. Our approach was based on community "best practices" by using proven technologies and expertise coupled with technology transfer such as the U of ME/GOMOOS Buoys. Furthermore, partnering with WeatherFlow Inc., in the private sector has proven an efficient approach which constitutes a milestone for the IOOS program.

Strong regional partnerships have also been achieved through the implementation of CariCOOS. The Puerto Rico Sea Grant College Program and CariCOOS work closely in outreach and stakeholder engagement effectively widening the stakeholder base for both organizations. The PR Coastal Zone Management Program is an influential stakeholder that looks to CariCOOS for specialized data products. A formal MOA is now in place between CariCOOS and the NWS San Juan, two former CaRA interns are now employed at the San Juan WFO and numerical models initially developed by CariCOOS are now in operational use there. CariCOOS routinely consults with the US Coast Guard on buoy placement and other matters and the USCG in turn assists CariCOOS in validation experiments. CariCOOS was instrumental in assisting the USCG in the

establishment of the PR North and South Coast Harbor Safety and Security Committees by drafting the initial version of the new bylaws and convening preparatory meetings. Other partners in the private sector include the Club Deportivo del Oeste, on the west coast of PR, La Regata, a nautical newspaper that provides an outreach vehicle for recreational stakeholders, and the West Indian Company, assisting buoy operations in the US Virgin Islands.

3 Leadership Personnel and Organizational Structure

Professor Julio M. Morell, the CariCOOS Executive Director, is assisted in his duties by Associate Directors Dr. Jorge E. Corredor and Dr. Miguel Canals. In addition to administrative duties, Dr Corredor coordinates water quality sampling and buoy maintenance and Dr. Canals coordinates wave and current measurements and sampling, the beach erosion program and model validation exercises. Dr. Yasmín Detrés devotes 50% of her time to CariCOOS education and outreach. Dr. Jorge E. Capella coordinates DMAC and GCM modeling activities, Dr. Stefano Leonardi implements HYCOM/ROMS modeling in support of CariCOOS port and harbor operation support program. Professor A. Mercado continues efforts towards development of a storm driven coastal inundation catalog. In the US Virgin Islands, Professor Roy Watlington serves as CariCOOS outreach coordinator. Office administration is the responsibility of Ms. Vanessa Gutierrez. Information technologist José B. Rodriguez maintains HPC infrastructure and Web Master Adolfo Gonzalez curates CariCOOS and CaRA web pages. Graduate and undergraduate student interns participate in field sampling programs, modeling activities and data product construction and maintenance.

4 Budget Analysis

Following the identification of a significant disparity between UPRM-R&D Center and CariCOOS project shadow account balances, CariCOOS procured the services of Ms. E. Larracuente to review account movements. In her analysis, Ms. Larracuente identified incomplete entry of rollover (unspent) funds into CariCOOS internal accounting yearly sheets as the explanation for said disparity and the unspent balance of $ 49,776.62 at the project end. A delay in carrying out the final reconciliation, at least partly attributable to the recent adoption of extremely itemized accounting software (UFIS) by UPRM R&D Center, precluded identification of the accounting error before final closure of the account.

5 Issues

As per above budget analysis.