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14. ABSTRACT

The Bio-Optical Forecasting (BioCast) System is a model that provides the U.S. Navy with short-term forecasts of the ocean's optical environment. These forecasts are used to support a broad spectrum of naval operations. BioCast ingests satellite surface optical properties and 3D ocean model velocity forecasts and calculates a three-dimensional optical property (pseudo-tracer) transport. BioCast verification statistics generated via forecast comparison to "next-day" satellite images show superior performance over 24-hour persistence of composite satellite data. Future updates include integration of 3D optical property as initial state and complex bottom sediment models for nephloid layer.

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Table of Contents

1 Introduction

Work completed under the *Modeling, Sensing and Forecasting Ocean Optical Products for Navy* project provides naval operations with new and enhanced predictive capabilities for the Tactical Ocean Data System (TODS) implemented at NAVOCEANO. TODS provides fusion of satellite imagery, METOC models and *in situ* observation products (i.e. gliders) that is subsequently coupled to Navy performance models to produce target and/or asset performance surfaces. The system components (*Display, OpCast/BioCast, 3DOG, and MIW System Performance Surfaces*) provide both real time and forecast characterizations of two and/or three dimensional battlespace used to produce warfare performance surfaces depicting ocean optical and physical properties as well as visible target detection. TODS currently produces:

1. the performance surface for the MIW underwater laser imaging systems (AN/AQS-24) and airborne systems (ALMDS)
2. the swimmer performance surface for underwater diver visibility and diver vulnerability for MIW and EXW missions
3. the performance surface for deployment of active and passive EO bathymetry systems (CHARTS and Passive EO satellite systems)

Previous transitions from this project include the TODS *Display*, *LAGER* – quality control software for glider optics data, and *OpCast*, a two dimensional optical forecast model. The transitioning element described by this VTR is *BioCast*, a three dimensional optical forecast model, which maintains the ability to generate two dimensional optical outputs.

Future transitions will include the 3D Optical Generator (3DOG) *which produces 3D optical volumes that feed the BioCast v2.0*, and the AQS-24 performance surface model. An upgrade to BioCast (v2.0) is planned for transition in FY14.

This Validation Test Report (VTR) provides the technical bases to transition BioCast version 1.0 and its improvement over the previously delivered OpCast to the NP3 Ocean Optics branch of the Naval Oceanographic Office (NAVOCEANO).

2 System Description

BioCast is an automated system for producing forecasts of oceanic bio-optical properties. It produces hourly forecasts up to n hours (limited by the model duration?) by coupling Automated Optical Processing System (AOPS) produced bio-optical products with Navy Coastal Ocean Model (NCOM) ocean current products to predict how the current models will affect the future optical environment. Currently, each forecast is a two-dimensional field representing the bio-optical properties of the region of interest defined by the AOPS input file. BioCast is designed to solve for the three-dimensional advection-diffusion-reaction (ADR) of dissolved or particulate tracers *(biological or chemical materials)* in aquatic environments. It requires a set of flow

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fields *(North/South and East/West velocity components)*, bathymetric data, an initial property field *of the parameter of interest*, and a user-specified spatial grid. The advantage of BioCast is that it rapidly solves the ADR of tracers significantly faster than fully explicit coupling with an ocean circulation model. The computational savings is very attractive for a wide range of forecasting applications and basic oceanographic/aquatic research programs.

A conceptual overview of forecasting the distribution of bio-optical properties using BioCast is provided in Figure 1. In this example, satellite imagery representing the beam attenuation coefficient ($_c$) at 531nm is combined with the flow fields generated by the NCOM model. The initial "Seed" image (*i.e. representing today's beam-c field*) is combined with today's NCOM hourly forecast currents to predict the turbidity distribution ($_c$)[1] in 24 hours. The following day's satellite beam-c image is compared with the forecast to determine the uncertainty or difference. The software is designed to run daily in automated fashion, providing a new capability for navy METOC operations by extending the utility of operational satellite image products. Additionally, the model evaluation uses the next day satellite image to provide a "self-checking" or reliability index of the forecast product.

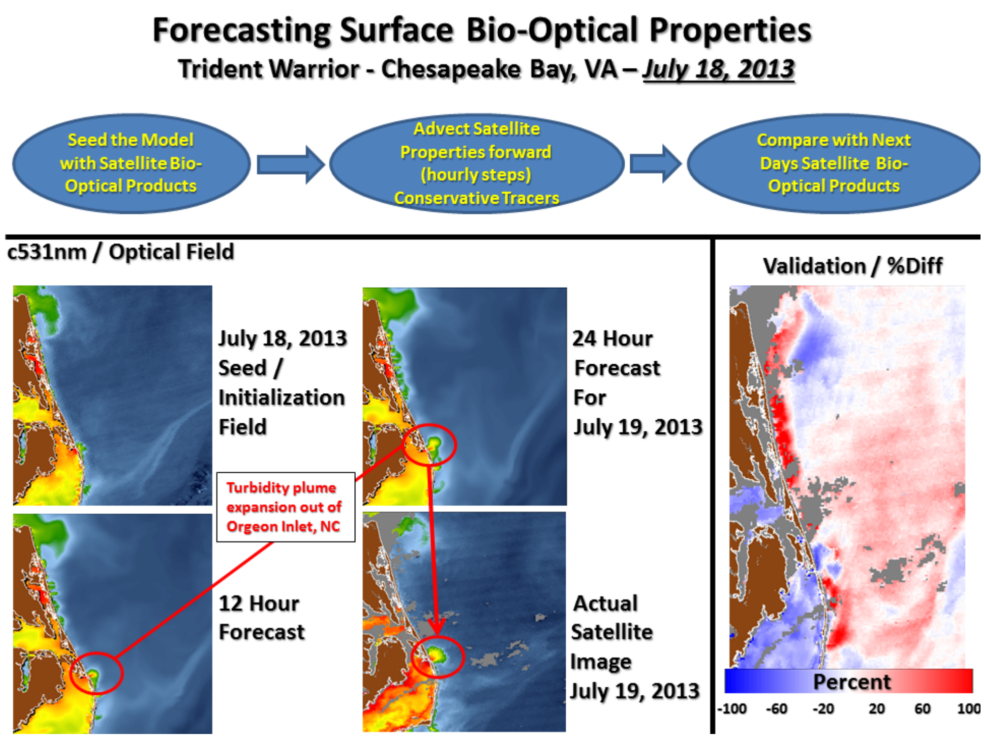

Figure 1 - Example of BioCast processing for Chesapeake Bay, Virginia during the Trident Warrior exercise using the MODIS satellite product for the beam attenuation (*proxy for turbidity*) coupled with the currents derived from the NCOM, BioCast enables the currents to advect the turbidity pixel information, generating a picture of future turbidity distribution. Differencing the BioCast product from the actual next day's image provides insight into the uncertainty of the BioCast model.

[1] The turbidity concentration represented by optical beam attenuation coefficient ($_c$) is used in this example, however other optical products could be used.

2.1 System Requirements

The BioCast software produces a prediction of optical conditions in all parts of an area of interest. It is designed to run on the Linux operating system, requiring a UNIX-like environment with the availability of shell scripts, command line utilities, and a cron scheduling system. The system is built around a framework of shell scripts which provide a high-level interface to the low-level functionality provided by binary executables written in *C* and Fortran. Users should be familiar with UNIX; BASH shell programming; and remote sensing, *particularly regarding computer processing of satellite data*, and ocean modeling.

Configuration of the system is accomplished by setting environment variables in “area” scripts. By setting the appropriate environment variables, every aspect of the operation of the BioCast system is controlled.

2.1.1 Data Input

BioCast requires data inputs from two primary sources, AOPS bio-optical products and relocatable NCOM current fields (COARDS compliant NetCDF format). In situ data acquired from ocean gliders or Battle Space Profiler (BSP/AEP) greatly enhance the forecasting capability by allowing expansion to three dimensional modeling[2].

Specific inputs include:

1. satellite ocean color imagery: MODIS-Terra, MODIS-Aqua, VIIRS
2. numerical models: relocatable NCOM (NCOM-RELO)
3. in situ data: physical and optical glider data[3] and BSP/AEP data

2.1.1.1 Satellite Ocean Color Imagery: AOPS Bio-Optical products

The bio-optical product for BioCast is produced by the Automated Optical Processing System (AOPS) v4.2 *or later* and is in the native Hierarchical Data Format (HDF)[4] produced by that system (Martinolich, 2006), e*xamples of the AOPS output are given in* Figure 2 *and* Figure 3. AOPS automatically handles all stages of calibration, atmospheric correction, application of oceanographic algorithms, warping to a geographic area of interest, compositing, and creation of quick look browse images. The geographic coverage area and spatial resolution are defined by attributes within the AOPS HDF file and the subsequent

[2] Optimization of the three dimensional capability is beyond the scope of this transition however it will be addressed in the transition of the 3-Dimensional Optical volume Generator (3DOG) component of the Tactical Ocean Data System (TODS) project, scheduled for transition in FY2016.

[3] quality controlled with LAGER – transitioned FY2011

[4] An intermediate stage exists in the Biocast data processing flow to convert the HDF files produced by AOPS into NetCDF, since Biocast can only read NetCDF formatted files; however, this conversion is performed automatically as needed by the Biocast system.

forecast is performed on this grid. BioCast can produce a forecast for any environmental parameter that AOPS can generate such as: total absorption (a), backscattering (b_b), chlorophyll (chl), sea surface temperature (SST), diver visibility, etc.

The advection software in BioCast requires a completely filled-in image to initiate advection (Figure 4). As BioCast cannot advect empty pixels in satellite image, once an image is chosen, a script is executed to generate a "seed" image that is completely filled in. The seed is created using previous days forecast if the environment variable is set for the directory location of forecast outputs. If the forecast directory is not set then the seed is generated using a limited iterative nearest neighbor triangular interpolation procedure (Casey, et. al., 2007). The first stage starts with the imagery from the target day and determines if the forecast directory is set. If set, then the contaminated pixels in today's image is filled with yesterday's forecast. If the forecast directory environment variable is not set then the limited triangular interpolation technique. is used to fill in image.

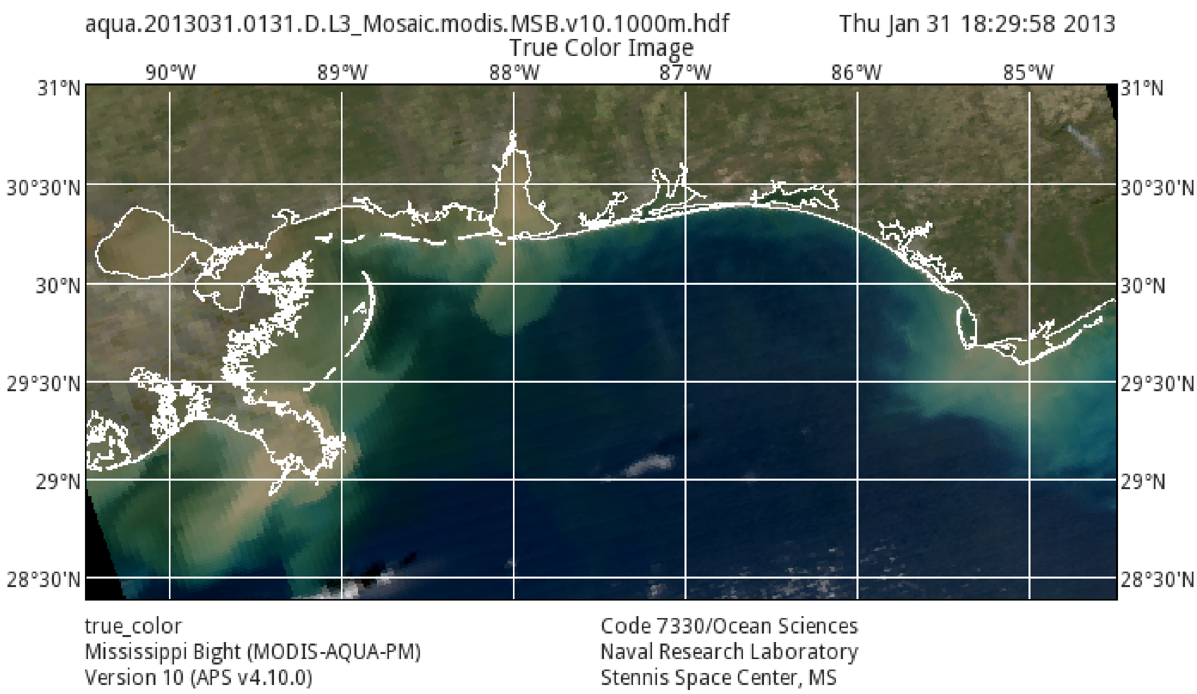

Figure 2 – Example of a MODIS Aqua true color image for January 31, 2013 generated using AOPS v4.8.

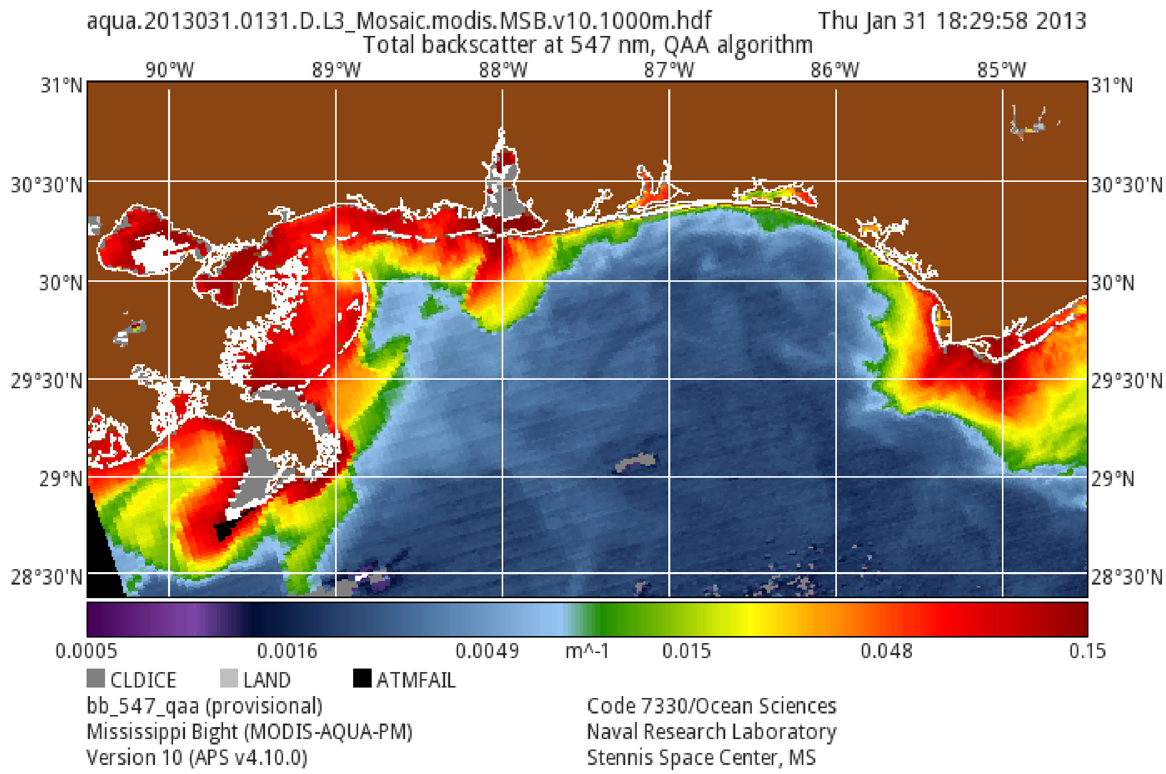

Figure 3 – Example of the backscattering optical product at 547nm from AOPS v4.8 (MODIS Aqua, for January 31, 2013). Notice the data holidays (grey pixels) resulting from various remote sensing processing flags such as failure of the atmospheric correction . Black areas are masked due to atmospheric failure and no coverage.

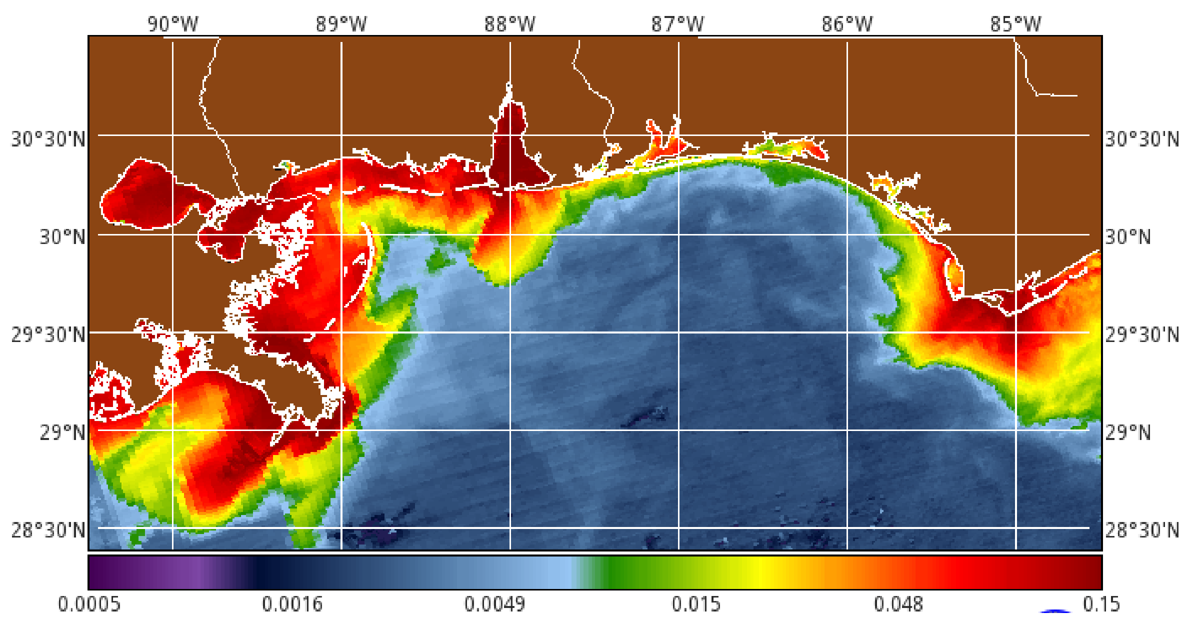

Figure 4 – Example of the backscattering at 547nm completely filled seed image (MODIS Aqua, for Jan 31, 2013), all pixels have an assigned bb 547nm value. A filled 'seed' image is a requirement for advection via BioCast.

2.1.1.2 Numerical Models: Relocatable NCOM current fields

The physical current field is produced by the Relocatable Navy Coastal Ocean Model (NCOM) and to be represented as ‘***u***’ and ‘***v***’ components in the standard COARDS NetCDF file format (Figure 5, example NCOM data set). The NCOM model is described in *Martin, 2000*. Relocatable NCOM is the relocatable version of the Navy Coastal Ocean Model optimized for limited geographic areas. The spatial grid of the current field is interpolated to match the grid as defined by the AOPS HDF file. The accuracy of the forecast product is dependent on the spatial and temporal resolution of the model fields.

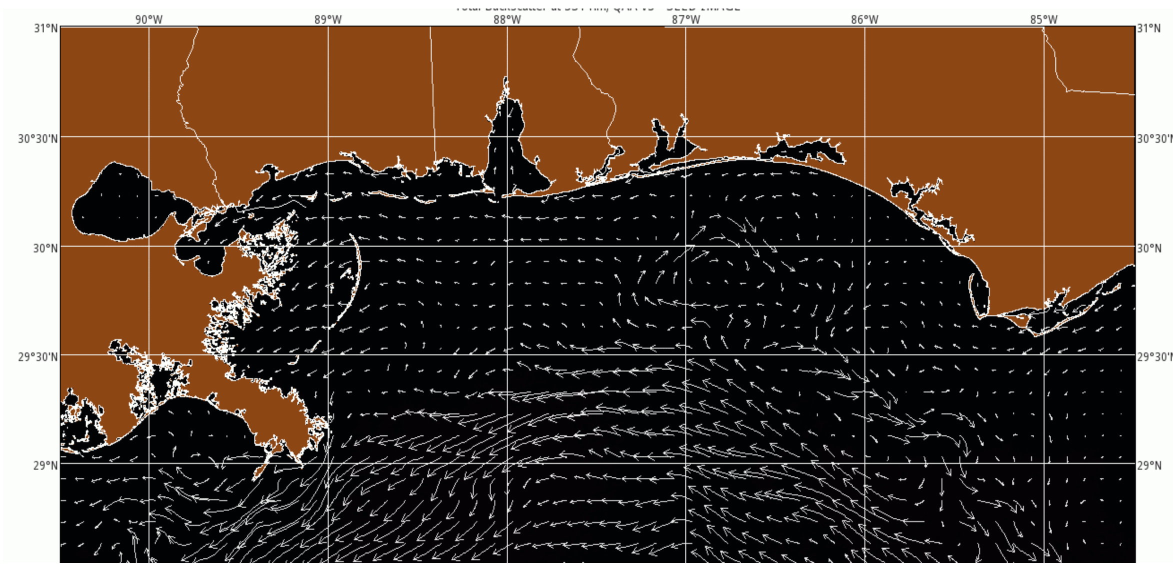

Figure 5 - Modeled surface current vectors (RELO NCOM)

2.1.2 Data Output

The output of the BioCast system is a set of files in NetCDF format, where one NetCDF file is created for each time step (configurable). The temporal frequency for output may be adjusted to accommodate hourly resolution. The geographic dimensions will match those of the input AOPS HDF file.

Outputs from these transitions will advance and deliver near real time high resolution fused and integrated oceanographic products which can be used to support a variety Navy missions especially MIW, and LIDAR operations. The products include 1) a 2D/3D forecast of coastal ocean optical properties to support performance surface efforts, 2) a performance surface of the laser imaging systems (*the AN/AQS-24 performance surface has already been packaged into the TODS system*) 3) swimmer performance surface (visibility and vulnerability), 4) performance surface for laser system (eg. ALMDS), and 5) a performance surface for deployment of active and passive EO bathymetry systems (CHARTS).

2.2 Important BioCast Caveats and System Limitations

2.2.1 Bathymetry

BioCast uses information from ocean circulation models to describe the three-dimensional transport of optical properties. In this sense, the operational ocean circulation models (such as NCOM and HYCOM) are the "parent" models and BioCast is a "child" model. This is an important conceptual paradigm because if significant changes are made to the physical domain of BioCast (the child) that are very different from the parent then large errors and/or model failure can occur. For example, three-dimensional ocean current velocities are mapped from the parent model to the child model over the same geographical area. BioCast constrains these velocities to observe continuity, and as a result, conservation of mass. This keeps the optical properties positive-definite and preserves a reasonable forecast solution. If, however, the bathymetry used in BioCast (the child model) is significantly different from the bathymetry used in the parent model, then BioCast may be unable to preserve flow field continuity. This may result in numerical instability and model failure.

Our testing and design of the system suggests small discrepancies in the bathymetry will not cause any significant problems. In fact, several fail-safe mechanisms are built into the numerical code to prevent model failure in the event of small numerical instabilities. However, if a very-high resolution bathymetry is used (to include topographic irregularities) in the child model whereas a low-resolution, coarse (or smoothed) bathymetry was used in the parent model, then the system will likely fail. This is because large changes in the bathymetry will cause accelerations in the fluid flow in order to maintain hydrodynamic continuity. If these irregularities were not accounted for in the parent hydrodynamic model, the child model will be unable to adjust the global velocity fields in a reasonable fashion. The BioCast continuity adjustment is only valid and reasonable for relatively small velocity corrections.

BioCast also creates an identification of "land" points before it executes a forecast cycle. The code must identify "ocean" points adjacent to "land" in order to correctly perform the transport calculations. Any disagreement between the satellite image and the physical ocean model about where land is located will be resolved in favor of land. BioCast assumes that areas of zero motion (component velocities are both equal to zero) are land points. Once a point is identified as land – no transport at that exact location is calculated. This is normally not a problem if the land designation in the parent model and the satellite image are reasonably close. However, the user should be aware that if the satellite identifies (or the parent model) a large region of land not present in the parent model (or satellite) there will be no forecast in those locations.

2.2.2 Horizontal Scaling and Numerical Diffusion

Development and testing of the BioCast system has taken place primarily at horizontal resolutions of approximately 0.5 – 3 km. This is a typical horizontal resolution for regional ocean models as well as satellite ocean color imagery. BioCast utilizes a first-order, upstream numerical material transport scheme. This numerical method contains implicit numerical diffusion. In this case, this implicit diffusion is an advantage of the system: there is no need for explicit diffusive terms, numerical diffusion/turbulence closure schemes, and the associated computational costs. The amount of this implicit numerical diffusion is a function of the velocity, internal time step, and horizontal resolution. Given these variables at typical BioCast application values, and given the aforementioned horizontal resolutions, the BioCast numerical diffusion scales almost perfectly with the magnitude of natural horizontal eddy diffusion observed in the oceans (Obuko, 1970). This is the reason, in a qualitative sense, that the BioCast results also appear to be reasonable to the operator. However, at finer scales of horizontal resolution (~ 50 meters) the BioCast results may appear overly diffusive. Application at these finer scales will require calculation of anti-diffusive numerical fluxes or an alternate numerical transport scheme. It is strongly recommended that BioCast applications stay in the 0.5 – 3 km horizontal scaling range.

The current velocities from the physical model are used as input to solve for the numerical solution of material transport in the ocean. The current velocities and the rate of material transport are not identical. In the real ocean, material transport is a function of advection and turbulent diffusion. In the model, the transport is a numerical calculation of fluxes over discrete time/space increments and these flux calculations are inherently diffusive. As stated above, the numerical diffusivity and the natural expected rates of turbulent diffusion are appropriately similar over the scales of time and space used in BioCast. However, at current velocities >> 2 m s^{-1} the numerical diffusivity grows much larger than the expected natural diffusivity. This will have the effect of transporting and propagating materials much faster than would be observed in the real oceans. In addition, the numerical solution may become unstable because more material must flux out of a grid cell than the grid cell contains in a single time step. This would result in negative values of material concentration, which is physically impossible. For these reasons, we impose a material flux limitation at 2 m s^{-1}. This ensures numerical stability and constrains the numerical diffusion within reasonable limits.

2.2.3 The GIGO Principle

The initial release of the BioCast software is applicable to any user-defined tracer (satellite product). With this flexibility comes the caveat that there is no additional quality control check on tracer values. The system assumes the tracer is positive-definite (maintains non-zero and positive values across the domain), but there are no additional constraints. If the satellite image contains pixels with excessively high product values compared to the expected product value ranges, BioCast contains no internal quality control mechanisms and this value with be transported within the model. This may lead to spurious results in the forecast cycle. This is the Garbage In – Garbage Out (GIGO) principle. The user is responsible for cognizance of the GIGO principle and quality control of data streams fed into the BioCast system.

3 Validation Test descriptions

3.1 BioCast Processing

BioCast processing flow is controlled by a series of cron scripts, Figure 6. There are several stages to the processing. First a check is performed to ensure that the necessary data files exist. Then the seed generation procedure is performed, followed by the conversion of the seed HDF file to NetCDF format. Next a configuration file is generated and passed to the optical forecast executable to perform the forecast advection. Lastly the output, NetCDF files are moved to the configured output directory allowing the TODS display system to create quick look browse images.

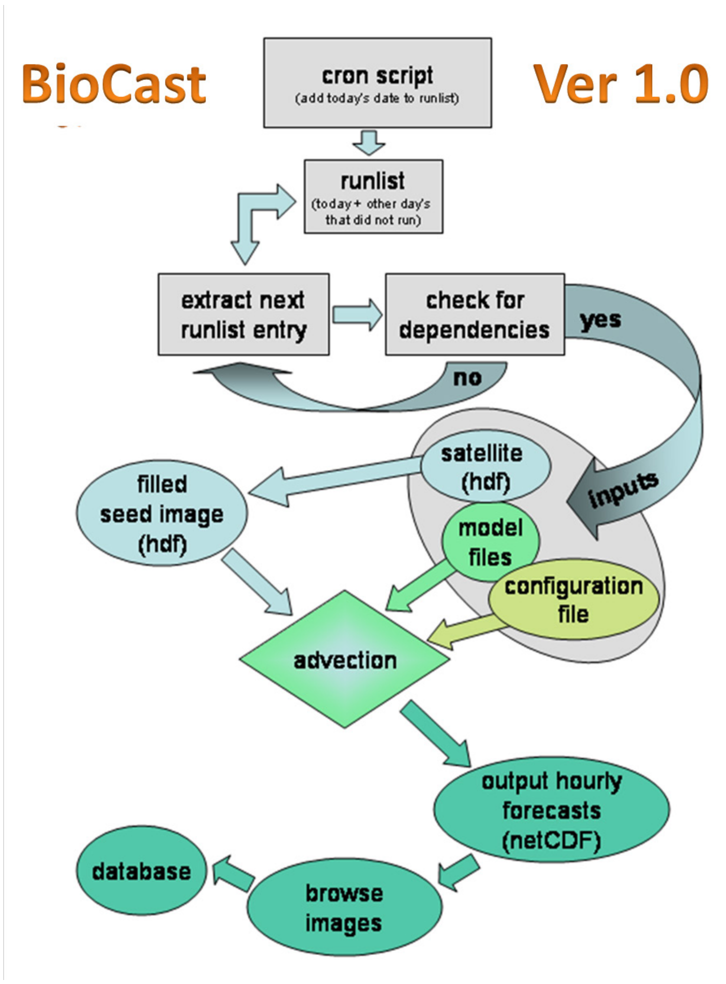

Figure 6 - OpCast process flow diagram

The top-level OpCast.sh script searches for the required data files. If it does not find all of the files, it exits with a non-zero status, which signals the cron.sh script that the particular date entry should not be removed from the run.list file and will try to run again the next time the cron is executed. If it does find all of the files, then it generates a configuration file and feeds it to the forecast program which performs the forecast and produces the results in a series of NetCDF files. After the forecast NetCDF files are produced, quick-look browse images are produced and the files are moved to their configured output directory. Once the procedure has completed successfully, the cron.sh script will remove the date entry from the run.list file.

3.1.1 Grid Space

Bathygen was developed and will be delivered with this version of BioCast. Bathygen allows the user to create a bathymetry file using the AOPS satellite grid/hdffile as input. The bathymetry grid is used as the primary grid for advection (note that the satellite and model grids are the same). If the modeled current fields are on a different grid, they will be interpolated to the primary grid. The boundary of the advection will be limited to the smaller of the two boundaries, *satellite grid or model grid* such that advection will not be performed outside of the data boundary. For example, if the satellite imagery fits entirely within the model grid, then every point within the satellite grid will have advection performed on it. If some part of the satellite grid falls outside of the model grid, then that portion of the satellite imagery will not be advected and the grid points will be flagged with the 'invalid' value.

Limitations on Maximum Grid Size: The maximum dimensions of the satellite and model grids are currently hard coded. The satellite grid cannot be larger than 3400 x 3400 and the model grid cannot be larger than 1500 x 1500. Should a requirement to process larger grid sizes arise, the hard coded limits can be raised, and the program recompiled.

3.1.2 Grid Type

Since the software currently makes assumptions about grid cells having a fixed area, and due to the current handling of navigation data, regular grids[5] are required. In addition to a regular grid, the software can handle grids whose navigation in one dimension does not change with respect to the other dimension, such as the Mercator projection.

3.1.3 Time Steps

The software currently performs advection temporally using discrete hourly time steps, therefore advection cannot be set for shorter time intervals, (*e.g. 30 minutes*). Additionally, if the chosen time step is of higher temporal resolution than that of the modeled current fields, then interpolation will be performed using the nearest temporally bounding current fields. When attempting to model oceanographic events, the time scale of the events should be considered and an appropriate advection time step should be chosen.

3.2 BioCast Validation

BioCast validation is completed in a six step procedure as described in Figure 7. Today's image (of any optical product, this example shows c 531nm) is obtained from the satellite. An initialization field is created, filling in gaps in coverage as required by the forecast model. This optical data initialization field is input into BioCast with the NCOM model forecast. BioCast advects the bio-optical property with respect to the predicted currents and ADR to produce a 24 hour forecast. The forecast is then compared to the data derived from the next day's image and a

[5] A pure regular grid is one in which the units of navigation increase by a fixed amount between each grid cell, sometimes referred to as equal-rectangular grid.

difference field is generated highlighting the difference between the measured and forecast property. Statistics are generated providing metrics for analysis.

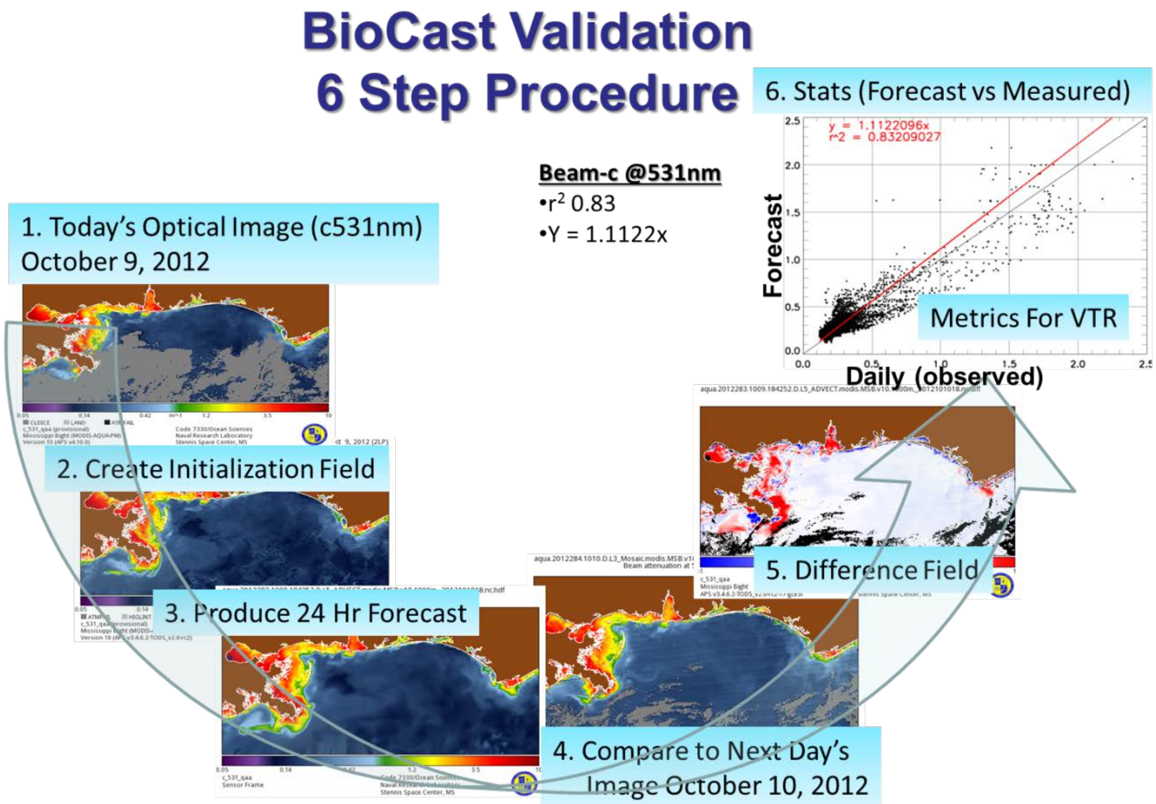

Figure 7 – BioCast Validation procedure. Today's image (of any product, shown here is c 531nm) is obtained from the satellite. An initialization field is created, filling in gaps in coverage. The optical data initialization field is input into BioCast with the NCOM model forecast. BioCast advects the bio-optical property with respect to the predicted currents and ADR to produce a 24 hour forecast. This forecast is then compared to the data derived from the next day's image and a difference field is generated showing the difference between the measured and forecast. Statistics are generated providing metrics for analysis.

3.3 Test Case 1: Mississippi Bight (from Dec 2011 to Oct of 2012)

3.3.1 Test Case 1 Set Up

Forecast runs were made for a ten month (Dec 2011 to Oct 2012) image sequence using MODIS Aqua 1km in the Mississippi Bight using both OpCast and BioCast. *Recall OpCast addresses surface advection while the BioCast is a 3D advection model.*

3.3.2 Test Case 1 Results

Figure 8 shows from left to right starting at the top, the mean absolute percent error (MAPE) for the OpCast model (top left) to the BioCast model (top right), allowing comparison of the two techniques. These were derived using the MODIS Aqua beam attenuation product (forecast vs. next day's image) from MODIS Aqua, December 2011 thru October 2012. The bottom panel below shows the results of subtracting the OpCast beam attenuation image from the corresponding BioCast results to give the difference field. The difference field is spatially variable showing conditions where both models outperform one another. Red indicates areas where the BioCast model produces superior results while blue indicates superior OpCast performance. The overwhelming red color indicates that BioCast is a better model and this is particularly true of the areas subject to dynamic mixing such as river plumes and areas of tidal mixing.

Figure 9 shows the mean distribution over the 11 month period of the MAPE for BioCast *(green)* and OpCast *(blue)* as a function of the percent total ocean pixels, *for BioCast 35% of the pixels have a mean absolute percent error from 0-4.9%*. Accumulating the errors for BioCast shows that for 74% of the pixels in the forecast image, the error is less than 15% where the error of less than 15% for OpCast is 68%. The overall BioCast improvement is seen in 70% of the total pixels.

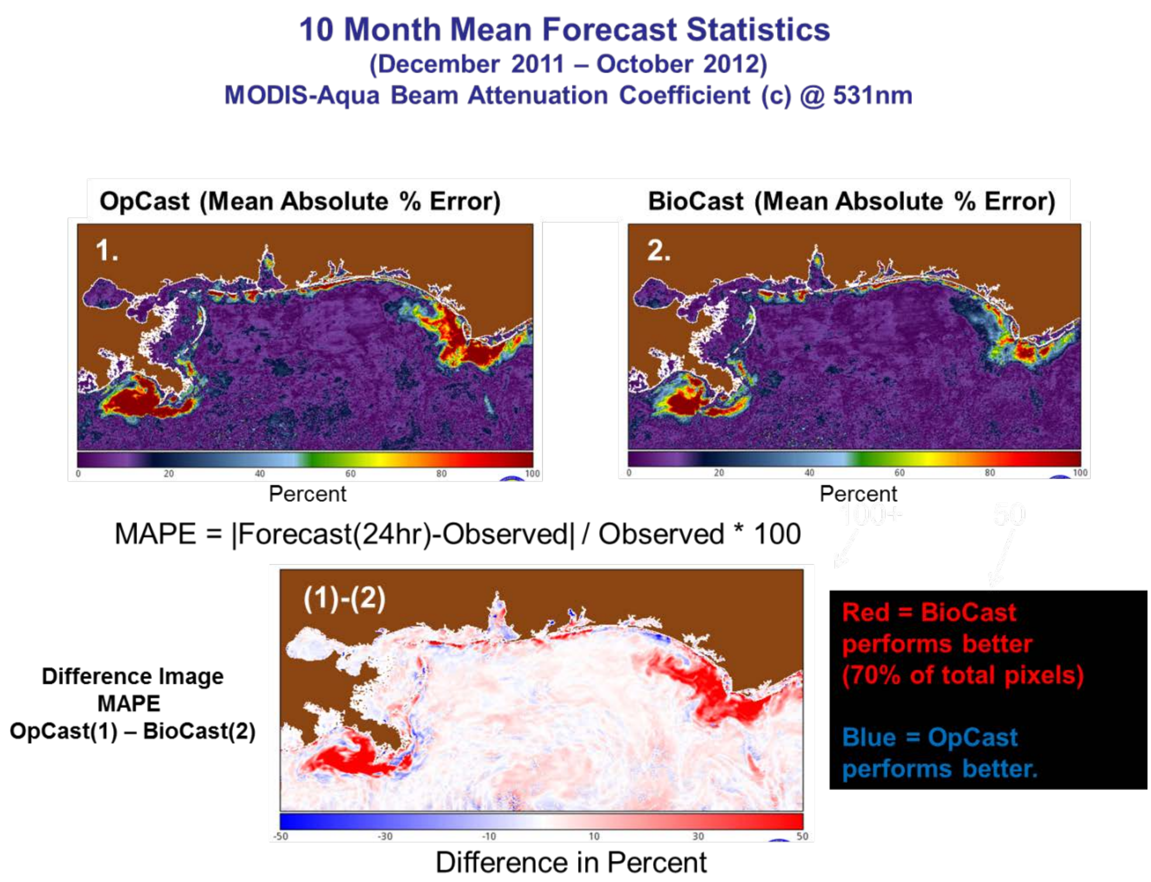

Figure 8 shows the mean absolute percent error (MAPE) over the 11 month period of the beam attenuation product from OpCast *(top left)* compared to BioCast *(top right)*. The bottom figure shows the difference between the forecast models, where the color is red -- BioCast outperforms OpCast. This visually shows BioCast outperforming the legacy forecast model in the dynamic coastal waters.

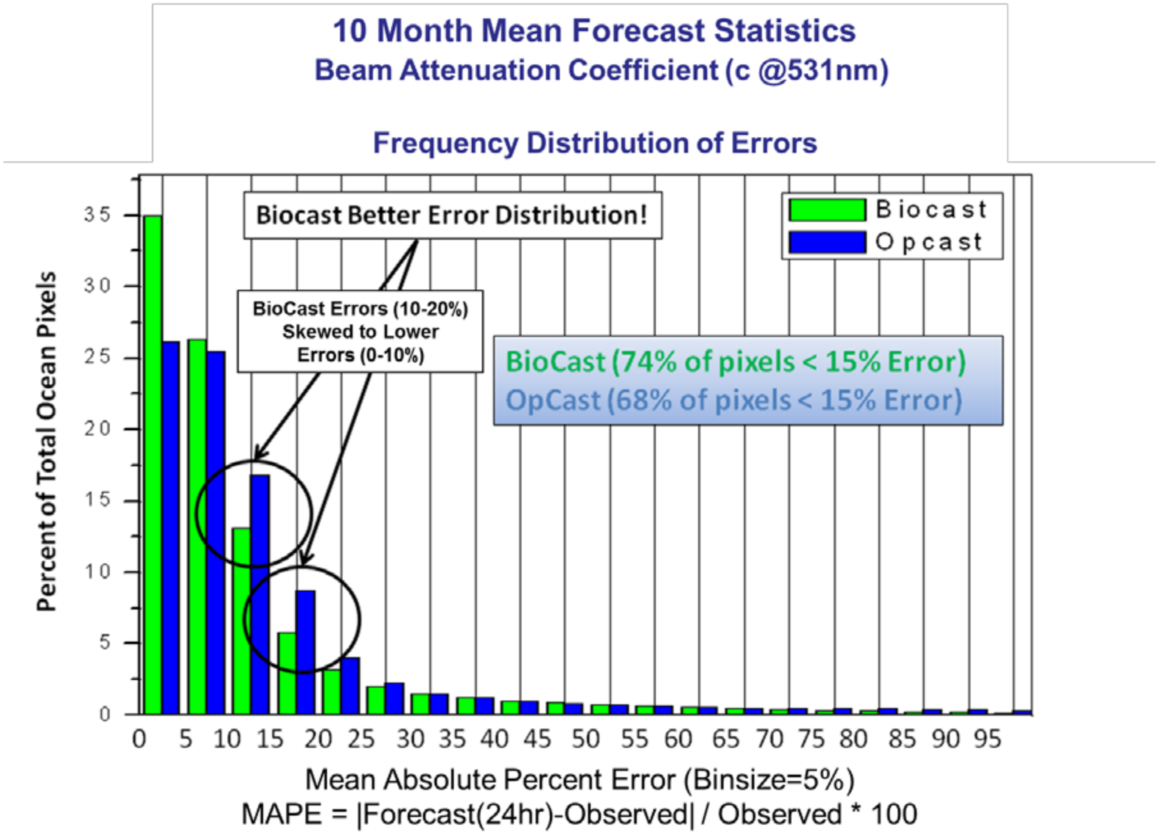

Figure 9 shows the distribution of the MAPE for BioCast *(green)* and OpCast *(blue)* as a function of the percent total ocean pixels, *for BioCast 35% of the pixels have a mean absolute percent error from 0-4.9%*. Accumulating the errors for BioCast shows that for 74% of the pixels in the forecast image, the error is less than 15% where the error of less than 15% for OpCast is 68%. The overall BioCast improvement is seen in 70% of the total pixels.

3.4 Test Case 2: Trident Warrior 2013

The objective of the Trident Warrior exercise was to utilize observations from unmanned air, surface, and undersea vehicles (UxVs) to assess the impact of in-situ observations on the representation and prediction of the Ocean Battlespace Environment and subsequent tactical impact on predictions of the electromagnetic (EM) propagation characteristics in the coastal marine atmospheric boundary layer.

NRL used this venue as an operational setting to test operational software that will soon be transitioned and deploy optical slocum gliders for ground truth and to evaluate the components of the Tactical Ocean Data System (TODS). We ran the 3D optical forecasting component "BioCast" along with the 3D Optical Generator (3DOG) in operational mode producing a snapshot of the 3D optical environment and 24 hour forecast. Products from the TODS system were accessible and used by operators in the field.

3.4.1 Test Case 2 Set up

The Trident Warrior 2013 (TW13) provided an opportunity to coordinate testing and demonstration of NRL-developed capabilities with Navy fleet experiment, in the Virginia Capes operating area inshore of the Gulf Stream. The experiment was conducted from July 13 – 18, 2013.

__Observing Platforms__:

5 days on-station R/V Knorr (AGOR-15) (sfc met, sst, current profiles, single station rawinsondes and sfc fluxes)
50 ScanEagle UAV Flight Hours (~10 sorties @50 Kts) (met profiles, sfc wave lidar)
4 Waveglider USVs (sfc met, sst, current profiles)
5 Scripps drifting wave buoys (sfc wave spectra)
1-2 NPS Flux Buoys (sfc met, sfc fluxes)
6-10 SLOCUM Seaglider UUVs (ocean temp, salinity, optical profiles)
R/V Knorr single station VHF/UHF/SHF/EHF radio range, power, SNR observations.
288 High density P-3 dropped AXBT observations before/during/after TW'13 Intensive Observation Period (IOP)

The collection of subsurface profile data using NRL SSC optical and physical sensors on unmanned underwater vehicles (UUVs/Gliders), was combined with real-time satellite-derived surface optical properties (collected at NRLSSC) and circulation models to provide nowcast and forecast optical properties and products of the entire water column using 3DOG. Half of the data collected was assimilated and half was put aside to be used for the 3DOG validation, Q3/4-FY14.

3.4.2 Test Case 2 Results

Episodes of observed expansion and contraction of surface optical isopleths against the U.S. mid-Atlantic coastline were well captured by the BioCast system during the Trident Warrior exercise. Rather than isolate all such cases with narrative detail, summary statistical measures are employed via comparison of the 24-hour forecast product with corresponding satellite data. In addition, persistence of present conditions is used a benchmark metric for the veracity of the forecasting system. Failing any available forecasting system, the next best predictor of conditions tomorrow is likely to be the conditions today. The inherent value of the forecasting system itself is thus evaluated with respect to the performance of persistence as a surrogate-forecasting tool.

To be sure, a single daily level 3 (L3)-mapped satellite product may contain significant areas of missing data due to clouds or atmospheric correction failure. Accordingly, the persistence values used were the 30-day latest image pixel composites rendered from the daily L3 images over the previous 30 days. The BioCast product (BC) and the 30-day latest-pixel composite persistence product (PS) were compared to the next-day satellite product, in locations where these next-day satellite data were available.

Statistics from the 61-day forecast cycling period (July 2013 – August 2013) were first described in terms of the Mean Absolute Difference (MAD):

$$MAD = \frac{1}{N}\sum_{n=1}^{N}|(F_n - R_n)| \quad (7)$$

where F is the forecast product and R is the reference product (the next-day image pixel).

Table 1 provides a summary of the MAD performance statistics for the beam attenuation (beam c)/ horizontal diver visibility products. BioCast reduces the MAD for $c_t(531)$ by an average of ~51% over the various pixel inclusive ranges from the coastline selected (10 – 249 km; Table 1). Beam-c values were also converted to horizontal diver visibility estimates to place the MAD statistics in more pragmatic terms. Again, the mean forecast field departure from observation is reduced by approximately half when BioCast is used in place of persistence.

Table 1 - Beam-c/Horizontal Diver Visibility MAD Performance Statistics

Range	10 km	30 km	60 km	109 km	209 km	249 km
C (531 nm) MAD Persist. (m^{-1}) x 10^{-2}	29.80	17.17	10.95	8.37	6.57	5.93
C (531 nm) MAD BIOCAST (m^{-1}) x 10^{-2}	17.80	8.00	4.88	3.78	3.08	2.76
BIOCAST-C (531 nm) Difference Reduction (%)	40.3	53.4	55.4	54.8	53.1	53.5
Horizontal Diver Visibility MAD Persistence (m)	2.30	3.98	4.13	4.32	4.29	4.26
Horizontal Diver Visibility MAD BIOCAST (m)	1.50	1.63	1.73	1.73	2.04	1.97
BIOCAST-Diver Vis. Difference Reduction (%)	34.8	59.0	58.1	60.0	52.4	53.8
N (number of comparisons) =	2532	11046	23039	35757	54110	65337

Another method of analysis is to compare forecast model results using statistical summary diagrams. These diagrams depend upon reproducible relationships between statistical quantities to summarize different aspects of forecast model performance. These relationships assume the underlying probability density function (pdf) of the variables is normal. Since the pdf of ocean surface optical properties is log-normal (*see* Campbell, 1995), these raw data were log-transformed and converted to a "grey scale" following: $GS[n] = \log_{10}(n) + 5.0$.

Performance statistics for BC and PS versus next-day imagery (R-reference) are first displayed on a normalized target diagram. The meaning of the target diagram is intuitively simple to understand: the distance of a point from the origin is equal to the Root-Mean-Square (RMS) difference between the forecast product and the reference vector:

$$RMS = \left(\frac{1}{N} \sum_{n=1}^{N} (F_n - R_n)^2 \right)^{0.5} \qquad (7)$$

where RMS is normalized by the reference standard deviation ($RMS^* = RMS/\sigma_R$). The closer the point lies to the origin (bulls-eye), the better the RMS* statistic (ideally, 0). The abscissa magnitude is the unbiased RMS* (or pattern RMS*) and the ordinate axis is the normalized bias, i.e., the difference between the mean of the comparison vectors. Further details may be found in Jolliff et al. (2009). For beam-c, PS values all fall in the RMS* range $0.5 < PS < 1.0$ (Figure 10a). This is within acceptable limits of forecast performance. Situations where RMS* values are greater than one suggest that a simple mean of the data would serve as a statistically superior forecast. In other words, the forecast model does not improve RMS-based statistical measures of performance over simpler maximum likelihood estimation techniques.

In contrast, BioCast (BC) target diagram performance measures (with the exception of the 10 km range) fall in the RMS* range of $u^* < BC < 0.5$ (Figure 10a). These performance measures lead to two conclusions: (1) BioCast provides a superior forecast product over persistence; and (2) there remains space for potential forecast improvements. The latter conclusion is based on our estimate of the RMS* uncertainty (u*). In theory, there must be some point where improved forecast-data agreement is no longer meaningful due to inherent uncertainties in the observations. $RMS^* = u^*$ is the estimate of this uncertainty horizon.

Another summary diagram format is the Taylor diagram (Taylor, 2001). These are polar plots that examine the relationships between the linear correlation coefficient (radial axis) and the Standard Deviation Ratio ($SDR = \sigma_F/\sigma_R$). The BioCast pattern measures (correlation and root variance) are all uniformly superior to the persistence pattern measures over all ranges from the coastline considered (Figure 10b). This means the spatial distribution of surface optical properties in the BioCast forecast product is closer to the patterns revealed in the next-day satellite images than persistence. This statistical result confirms our hypothesis that the satellite detected short-term (24 hr) variation in the surface optical property distribution is driven primarily by the ocean circulation.

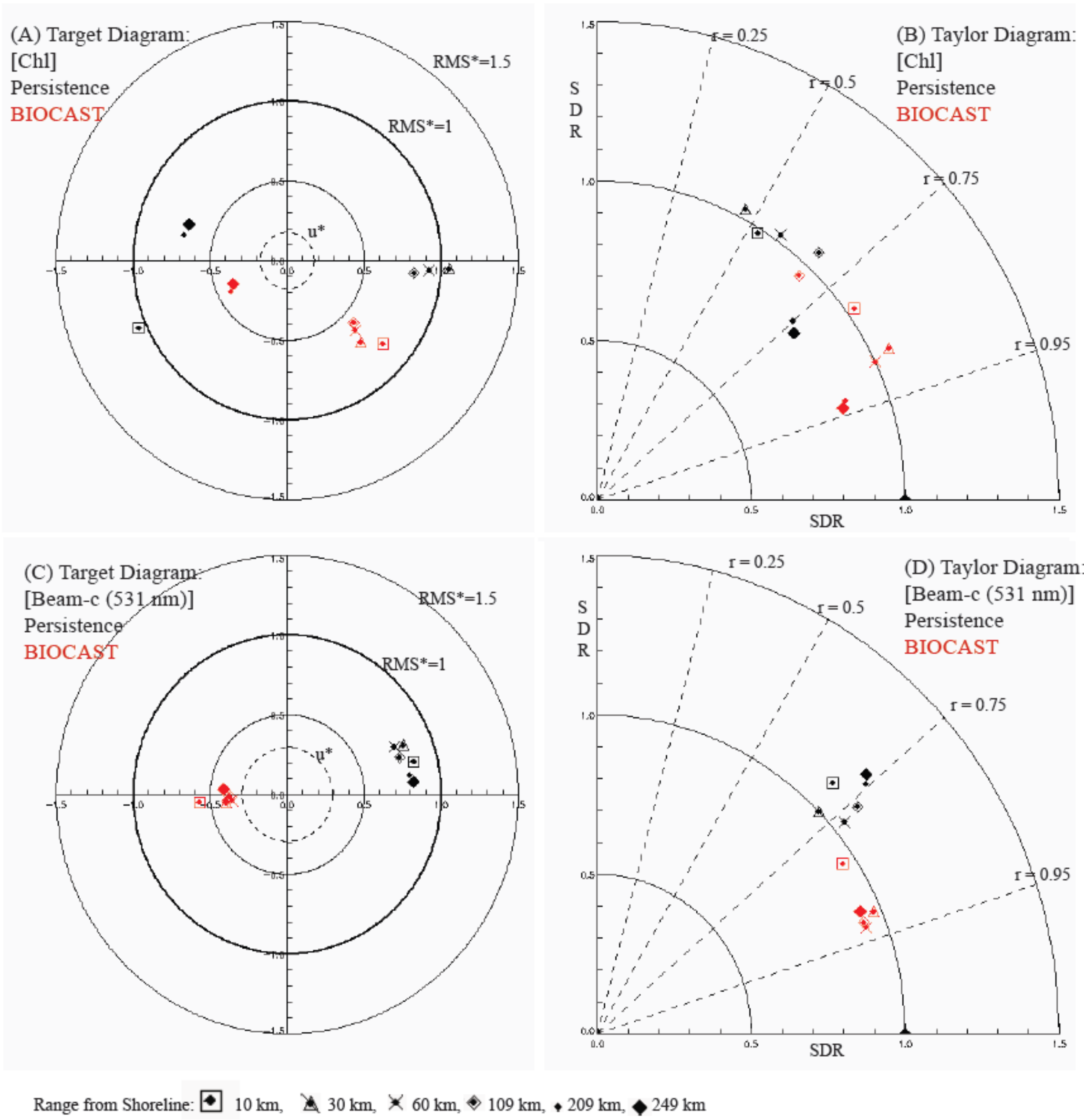

Figure 10 **Statistical summary diagrams comparing 30-day latest pixel composites (persistence) against the next-day MODIS satellite product (black) and BIOCAST 24-hour forecast against the same next-day MODIS product (red). Statistics are generated from 60-days of 'next-day' comparisons (1 July – 30 August 2013). The range refers to the subset of image pixels selected for statistical analysis using a distance from the shoreline criterion. Correlation (r) improves as the distance from the shoreline increases since the forecast products all mimic the general offshore bio-optical gradient. The target diagrams are a measure of bias (Y-axis) and unbiased RMS (X-axis). The distance from the origin is the total RMS score. Performance improves as the distance from the origin is diminished. BIOCAST points (red) fall closer to the origin than persistence points (black) (see A and C). Two points from the persistence set fall outside the RMS=1 marker (see in A). This indicates unacceptable forecast performance. Taylor diagrams are polar plots that summarize pattern-based statistics. The radial axis is the linear correlation and the ordinate axis is the ratio of standard deviations. The distance from SDR and r = 1 is the unbiased RMS. Performance improves as this distance is reduced. BIOCAST points are closer to this reference marker than persistence points (see B and D). Note: univariate statistical measures assume the underlying probability density function (pdf) is normal. Bio-optical properties have a log-normal pdf. Hence the raw data are log-transformed before the statistical analysis.**

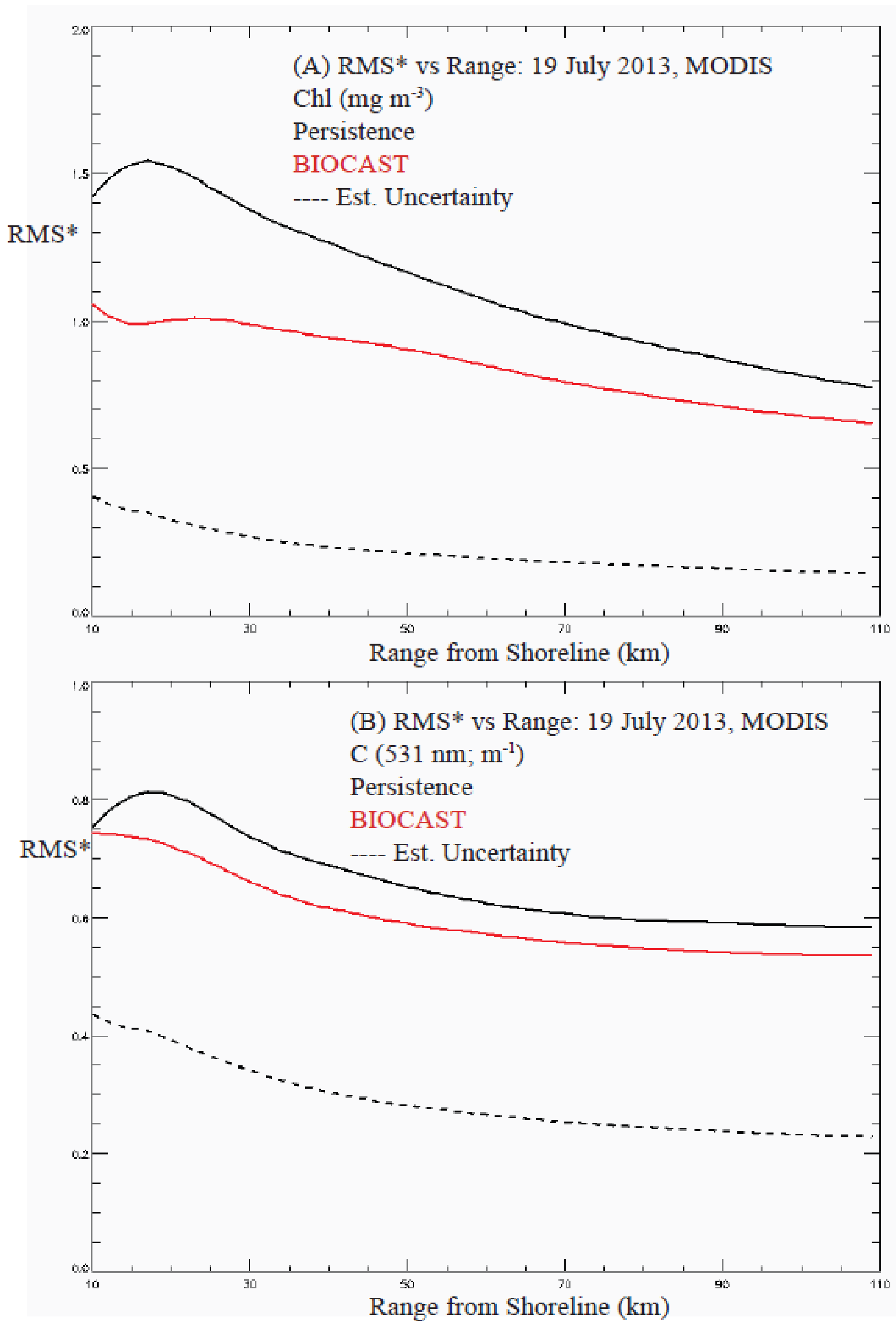

Figure 11 Statistical diagram comparing 30-day latest pixel composites (persistence) against the next-day MODIS satellite product (black) and BIOCAST 24-hour forecast against the same next-day MODIS product (red). Statistics are generated from the 'next-day' comparison to 19 July 2013. The range refers to the subset of image pixels selected for statistical analysis using a distance from the shoreline criterion. RMS* is the Root-Mean-Square Difference normalized by the standard deviation of the reference dataset (the next-day image). The RMS* uncertainty is estimated by comparing the reference dataset to the same dataset deliberately geo-referenced two image pixels away from the original. Note: univariate statistical measures assume the underlying probability density function (pdf) is normal. Bio-optical properties have a log-normal pdf. Hence the raw data are log-transformed before the statistical analysis.

4 Operational Implementation

4.1 Operational Concept

The TODS system and its components including BioCast will reside with NP3 at the Naval Oceanographic Office where it will be used to automatically produce near real time high resolution fused oceanographic products supporting a variety of Navy missions. The products will be used to support MIW exercises and operations but could easily support a variety of shallow water Navy missions (NSW, ISR, ASW and EXW). TODS support during Navy exercises and operations requires availability of oceanographic models and satellite imagery. The performance is enhanced when glider data is also available.

The final products will be disseminated via NAVOCEANO's web portal and other avenues compliant with DoD data distribution policies.

4.2 Resource Requirements

Current Systems at NAVOCEANO (A2/SAN) were upgraded during the initiation of this project and deemed sufficient. No additional resource requirements have been identified at the time of this writing.

4.3 Future Work

BioCast performance metrics for the 24-hour forecast sequence have been established for ten months of continuous daily forecasting sequence trails in the northern Gulf of Mexico and the two months during the Trident-Warrior, 2013 U.S. Navy exercise. BioCast is merely one aspect of the overall TODS capability: additional advancements in ocean optical forecasting will result from the integration of BioCast with other TODS components such as 3-Dimensional Optical Generator (3DOG).

3DOG can provide estimates vertical variations in optical properties. This software utilizes *in situ* data sent from autonomous underwater vehicles (AUVs) to derive statistical relationships between vertical optical variability (departure of the subsurface optical property values from the surface value) and density variations in the water column. These empirically based optical property-density relationships are then projected to a three-dimensional field using: (a) the AOPS satellite-radiometer products for the surface optical values, and (b) analysis fields from data-assimilative and operational ocean models for the three-dimensional density field over a specified ocean region.

The final step in this performance field estimation technique is to link the vertical optical profiles with a system performance model. The model will be used to estimate the performance of the helicopter-towed AN/AQS-24 mine hunting system under a variety of optical conditions.

Forecast variations in the 3D optical field combined with the performance field model can provide a basis for determining optimal tow heights (above the bottom) and go-no-go scenarios at set tow heights for the AN/AQS-24 host platform. The AN/AQS-24 system is towed by an MH-53E Sea Dragon flown by the U.S. Navy's Helicopter Mine Countermeasures Squadrons (HM-14 "Vanguard" and HM-15 "Blackhawks").

BioCast will be integrated into the TODS performance field capability to provide and not limted to a 24 to 48 hour forecast of AN/AQS-24 system performance fields. This is precisely the type of information that can enter into the tactical planning of naval missions, and it thereby completes the chain of research from first principles and basic science to accurate forecast products that support the U. S. Navy and Marine Corps team.

5 Summary and Conclusions

NRL's initial assessment of the optical forecast generated by BioCast is of high enough quality to produce reasonable results. The BioCast model is shown to be capable of generating operational quality data in a time frame that supports the military demand. Available imagery systems perform well as does the forecasting capability of the NCOM model. Results indicate BioCast should provide an extension of the current optical products produced by NAVOCEANO NP3. The model output appears reasonably well characterized however remain subject to the uncertainty inherent to the input data sources. Continuous Cal/Val procedures are recommended to monitor imagery sensor performance and product data to keep a handle on uncertainty in those data sources. Advances in quantifying uncertainty in ocean models will improve the performance of BioCast and the TODS system as a whole.

Meteorological forecasting has been shown to have a critical impact on mission success. Similarly ocean predictions can be a critical enabler for naval operations. The BioCast model can be used for characterizing the physical environment by coupling current forecasts with current state biological or sediment properties to forecast coastal conditions such as water optical properties, biological properties, suspended sediments, water clarity (e.g. diver visibility and laser penetration). Based on initial validation results, we recommend proceeding with operational implementation of BioCast. Although further analyses and improvements will be required, BioCast marks another milestone in the implementation of the Tactical Ocean Data System capability at NAVOCEANO.

6 Acknowledgements

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8 List of Acronyms

3DOG - 3-dimensional Optical Volume Generator
a - total absorption
ADR - Advection Diffusion Reaction
ALMDS – Airborne Laser Mine Detection System
AOPS - Automated Optical Processing System
ASW - Anti-Submarine Warfare
b_b – optical backscattering coefficient
BSP - Battle Space Profiler
CHARTS - Compact Hydrographic Airborne Rapid Total Survey
Chl - Chlorophyll
EO - Electro Optical
EXW - Expeditionary Warfare
HDF- Hierarchical Data Format
ISR - Intelligence surveillance Reconnaissance
LIDAR – Light Detection and Rangins
MAPE - Mean Absolute Percent Error
METOC - Meteorology and Oceanography
MIW - Mine Warfare
MODIS - Moderate Resolution Imaging Spectroradiometer
NAVOCEANO - Naval Oceanographic Office
NCOM - Navy Coastal Ocean Model
NRL - Naval Research Laboratory
NSW - Naval Special Warfare
SPAWAR - Space and Naval Warfare Systems Command
SST - sea surface temperature
TODS - Tactical Ocean Data System
VIIRS - Visible Infrared Imager Radiometer Suite
VTR - Validation Test Report