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SEA STATE AND WEATHER ASSESSMENT CAPABILITY FOR NASA'S CONSTELLATION PROGRAM

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Abstract

Marine weather and related parameters such as wind, ocean wave height and period, air temperature, sea surface temperature, visibility, and potential for icing are critical to the design, operation, and safety of crewed space vehicles. The National Aeronautics and Space Administration's (NASA's) Constellation Program requires detailed assessment of marine weather related parameters that may be encountered during launch, abort, landing, and crew rescue operations for the crewed Ares/Orion space vehicles. This information is required for both space vehicle design and operational purposes. The space vehicles must be designed such that they can withstand the environment they are likely to encounter. The crewed Ares/Orion space vehicles will launch from NASA's Kennedy Space Center (KSC), Florida for both International Space Station (ISS) missions with 51.6^{o} inclination orbits and lunar missions with approximately 28^{o} inclination orbits. Since both missions will fly over the Atlantic Ocean on ascent to orbit and will fly over the Pacific Ocean on descent from orbit, an unlikely but possible emergency abort could require parachuting the Orion capsule and crew into the ocean. This situation could potentially put the crew in an isolated and hazardous environment for several hours while they await rescue. Therefore, abort, landing, and crew rescue elements of the Constellation Program must address weather related parameters on a global scale. This paper describes buoy measurement data, sea surface temperature satellite data, and sea state computer model data that are being utilized by the Constellation Program to address these design and operational issues.

1. INTRODUCTION

The National Aeronautics and Space Administration's (NASA's) Constellation Program's crewed vehicle is currently being designed for future spaceflight to the moon and Mars. The crewed vehicle, named Ares, is designed similar to the Saturn V rocket used in the Apollo missions as it contains a capsule, named Orion, to hold the crew. Ares will launch from Kennedy Space Center (KSC), FL on a 28° inclination orbit for Lunar Missions and a 51.6° inclination orbit for missions to the International Space Station (ISS). Both of these orbit inclinations require Ares to fly over the Atlantic Ocean during ascent to orbit. During the unlikely but possible event which would require an emergency abort during ascent, Orion would jettison from Ares and land in the water. In addition, Orion is being designed to have the capability to land in the water on nominal re-entry. Thus, the sea states must be known for both nominal and emergency returns to the ocean.

Climatological and operational data sources provide sea state information to various facets of the Constellation Program. Orion design engineers need sea state climates to design the crewed vehicle to handle the expected sea conditions in the most efficient manner possible. Rescue and recovery operations need sea state data to decide ahead of time the best means to rescue the crew, and which ocean areas are the most hazardous. Other factors, such as distance from the rescue source, influence rescue operations along with the marine environment. In addition, rescue and recovery operations need operational sea state data to decide how soon they can rescue the crew and recover Orion. Operational sea state data can be utilized to determine if conditions are favorable for a marine landing in real-time, or if Orion can successfully avoid the hazardous region(s) (Garner et Al, 2006). Sea states also affect launch and landing probability. The marine climate in the region which the Orion vehicle could land influences the overall probability of launch or landing by determining whether or not the environmental conditions at the locations of interest are favorable for launch or landing operations.

This conference preprint addresses the sea state data capability for the Constellation Program. First, it references the different sea state parameters which apply to the Ares / Orion vehicle design and proposed operations. Next, a presentation of the data sources being used, their applicability to the Constellation Program, and their advantages and disadvantages are provided. Finally, this preprint discusses how the Natural Environments Branch at Marshall Space Flight Center (MSFC) uses sea state data from these different sources to provide the various stakeholders within the Constellation program the information needed for design and operation of the Ares

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and Orion space vehicles, along with rescue and recovery operations.

2. SEA STATE PARAMETERS

The characteristics of the sea state are reported by the various measurement and analytical sources as quantified parameters of significant wave height (SWH), wave period, wind speed, and temperature. The Constellation Program uses these parameters to decide the applicable marine environment in which to design the Ares and Orion vehicles and to perform rescue and recovery operations. This section outlines each parameter, and discusses the applicability of the parameter to the various aspects of the Constellation Program.

2.1 *Significant Wave Height*

The SWH provides a popular representation of the sea state, and applies to multiple areas within the Constellation Program. SWH is defined as the mean of the highest one third of the waves for a given wave spectrum. Both *in-situ* data sources (e.g., buoys) and numerical models report the wave height as the SWH. In addition, SWH typically corresponds to the height of the waves that are visually estimated by an experienced observer, and is what the literature uses to classify "sea state" (Caires et Al 2003, Sterl and Caires 2005). This parameter affects search and rescue (SAR) criteria for crew and vehicle recovery as well as the probability of launch while the vehicle is at the launch pad. It is highly undesirable to place SAR forces in a situation where they must attempt a rescue when the SWH or other criteria exceed their specified threshold. Likewise, if day-of-launch decision-makers determine that launch cannot occur if the SWH is above the threshold in critical areas of the flight path, the launch could be scrubbed.

Studies have shown that wave height frequencies follow a Rayleigh probability distribution, which can be used to derive useful statistics from the SWH. It is important to note that the SWH does not represent the maximum wave one could see. Using a Rayleigh distribution, the following can be derived:

$$H_{mean} = 0.63 H_s, \quad (1.a)$$

$$H_{1/10} = 1.27 H_s, \quad (1.b)$$

$$H_{1/100} = 1.67 H_s, \quad (1.c)$$

and $$H_{\max} \sim 2.0 H_s. \quad (1.d)$$

In Equation 1, H_s is analogous to SWH, H_{mean} is the average wave height, $H_{1/10}$ is the height of the highest one tenth of the waves, $H_{1/100}$ is the height of the highest one hundredth of the waves, and H_{max} is the maximum wave height for a reasonably large sample of (greater than 2000) waves. Figure 1 presents a graphical representation of these equations.

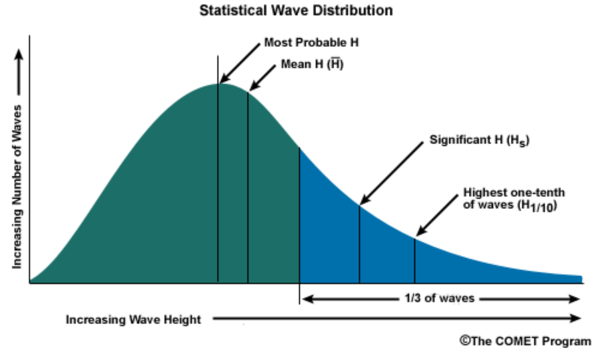

Figure 1: Rayleigh distribution of wave heights annotated with the relationships of H_{mean}, H_s, and $H_{1/10}$ (http://www.meted.ucar.edu/marine/mod1_wv_type_char/frameset.htm)

2.2 *Wind Speed*

In addition to SWH, wind speed is a readily available sea state parameter which applies to the Constellation Program. Wind speed is reported from various heights above the ocean surface, depending on the data source. Most buoys report the wind speed at 3 m or 6 m height, while numerical models typically output the wind speed at 10 m height. The wind speed is used in a similar manner to the SWH as it influences the probability of launch and landing versus given constraints given by the design and operations communities, including SAR. In addition, the wind speed is critical to the behavior of Orion's parachutes as the crewed vehicle lands in the water. Because these parachutes are not at the measurement height of the wind, a wind profile equation has to be applied to extrapolate the wind speed to the desired height. In addition to influencing the parachutes, the wind speed also influences the design of Orion itself as NASA engineers use it as an input to the Pierson-Moskowtiz wave spectrum (Pierson and Moskowitz 1964, Ewing and Laing 1987), which is currently being utilized to determine wave slope spectra for vehicle design.

2.3 *Temperature*

Orion's design also depends on both the air temperature and sea surface temperature (SST). Temperature data show regions of the globe where engineers are concerned that the crew may get so warm that they must perform post-landing operations, such as removal of their suits and / or opening a hatch for ventilation, in order to survive. In addition, temperature data is used in conjunction with SWH data to address conditions where the crew could need to perform post-landing operations, but would not be able to do so due to accelerations within Orion. De-conditioned crew (i.e., crew members which are fatigued and sick from re-entering Earth's atmosphere after a significant time in space) may not be capable of post-landing operations, and thus environments which might require the crew to perform these operations must be characterized. SST and air temperature measurements are typically taken at 1 m depth and 2 m above the surface, respectively.

2.4 *Wave Period*

The final raw data parameter which the Constellation Program needs characterized is the wave period, which is defined as the time it takes for successive wave crests to pass a given location. Ares and Orion design and operations communities utilize the wave period along with SWH to determine how rough the seas are, and thus if design and operations constraints will be met. In addition, the wave period is utilized by the Orion design community to determine if the seas will be too rough for an oceanic landing. The wave period is reported in various statistical forms, including the mean wave period, which is the average of the wave periods in the spectrum assuming the periods follow a Gaussian distribution (Corps of Engineers 2006). Here, the mean wave period is used to characterize the period of the waves in the regions of interest.

3. CLIMATOLOGICAL DATA SOURCES, PRODUCTS, AND LIMITATIONS

Available data sources can be classified in two categories: observed and modeled. The former mainly incorporates *in-situ* measurements from buoys and ships, as well as remotely-sensed measurements from satellites. The latter refers to gridded hindcast (and forecast) models, which utilize data from observed data sources as initial conditions, and extrapolate spatially and temporally using complex equations of motion and thermodynamics. Each data source reports specific sea state parameters at various heights and resolutions, and have respective advantages and drawbacks. The following subsections describe the climatological sea state data sources used by the MSFC Natural Environments Branch.

3.1 *Buoys*

Buoys contain the most directly-measured data at the finest temporal resolution; however a lack of spatial coverage presents a significant drawback. Most buoys report SWH, wave period, temperature, and wind speed on an hourly basis over a period of record (POR) which varies with each buoy. Data are directly obtained through instruments on the buoy, post-processed, and are made available online free of charge by the National Data Buoy Center (NDBC: www.ndbc.noaa.gov). The NDBC maintains a network of buoys around the globe, but the buoys are concentrated in the vicinity of the Continental United States. The quality of measurements can vary due to possible complications in the data acquisition and / or post-processing process for the individual buoy. However, the measurements usually go through an extensive quality-control (QC) process before the data is made available, and QC indicators are included in some buoy data reports. Despite the fact that buoys contain what could be called the "most reliable" sea state data, the limited number and locations of the buoys present a significant problem. Many times, design and operations engineers are interested in the sea conditions in regions which do not contain a representative buoy with an extensive POR. Therefore, buoy data cannot be used on its own to characterize the sea state environments for benefit of the Constellation Program. However, they can be used to assess the environment at a specific location if it contains an extensive POR. Buoy data can also be compared to data from other sources at it is widely considered to be "ground truth" (Caires and Sterl 2005).

3.2 *Voluntary Observing Ships*

Voluntary observing ships (VOS) provide a second *in-situ* data source. Sailors have been reporting sea state conditions for centuries, and in 1863 the VOS network was organized to accommodate these reports from the many ships at sea. Thus the VOS network database has the major advantage of containing the most extensive POR of all the sea state databases. Roughly 4000 ships are currently in the VOS fleet. More details on the VOS network can be found at http://www.vos.noaa.gov/vos_scheme.shtml.

Despite the large number of ships and extensive POR, the VOS network has several drawbacks when applied to the Constellation Program. First, ships are concentrated along major shipping routes. It is rare that a ship will venture into a region outside its proposed route and report the weather at that location. Second, most observations occur in calm to moderate conditions as the ships purposely attempt to avoid bad weather, which may make the conditions at a particular location seem more benign than the conditions that actually exist. The third and fourth major drawbacks of using the VOS database is that observation quality is highly subjective to the reporter's experience, and that observations are not very detailed. These drawbacks present obstacles to the Constellation Program, which needs robust climatolologies at various locations. In addition, the Constellation Program must know what the "worst case" conditions could be at a particular location. The VOS network could possibly, however, help operationally to supplement forecasts where the ground track of the Ares vehicle crosses a location with a VOS observation. Therefore, although the VOS network is essential for marine observations and forecast assistance, the Constellation Program cannot utilize this database alone to provide the necessary marine climatologies to successfully design the Ares and Orion vehicles as well as plan and implement recovery operations.

3.3 *Satellites*

In addition to *in-situ* data sources, measurements of the different sea state parameters are taken using remote sensing from satellites. Satellites contain sensors which indirectly measure variables such as surface elevation and temperature. These sensors take measurements continuously over a swath, or section, of the globe. The swath's size depends on the satellite's orbit and height above Earth's surface as well as the characteristics of the satellite itself. The measurements go through extensive QC processes to eliminate residual effects, including those from clouds and the satellite's beam angle, before the data can be interpreted. Satellites provide averaged sea state parameters, such as SST and SWH, for a specified POR, which depends on how long the sensor has been in operation.

The use of satellite data has advantages over buoy and ship data; however, a unique set of disadvantages refrain the Constellation Program from utilizing satellite data alone. Satellites provide good spatial coverage as swaths typically extend from a few hundred to thousands of miles. Buoys and ships, on the other hand, provide measurements at individual locations. In addition, the data from satellites is detailed and accurate provided the proper QC was performed. However, despite providing good data with an extensive spatial coverage, the spatial coverage is inhomogeneous as the swaths only cover sections of the globe. In addition, these swaths sometimes do not overlap. Satellites contain another drawback in that the POR of their data is comparatively short. These drawbacks make it difficult for satellites to provide the homogenous, extensive sea state information necessary for the Constellation Program to know the environments for which to design the vehicle and successfully implement rescue and recovery operations.

3.4 *Hindcast Models*

Despite the fact that it does not provide directly measured data, hindcast, or re-analysis, model data provide the desired sea state parameters at a favorable temporal and spatial resolution while utilizing observational data over an extensive POR. As seen in the previous subsections, observational data sources generally lack the temporal and spatial coverage desired by the Constellation Program. Using hindcast data, one can obtain applicable parameters at resolutions fine enough to discern an applicable climatology for a region which does not contain representative *in-situ* measurements.

Hindcast data provide the desired spatial and temporal coverage by interpolating and extrapolating the available observational data through time and space using complex equations of motion and thermodynamics. A general description of how hindcast models work follows. First, observational data, such as that from rawinsondes, buoys, and satellites, are provided as an initial condition. Next, the model is configured to interpolate and extrapolate the observational data at the desired spatial resolution at the initial time, providing a set of parameters on a grid. Then, the model extrapolates the gridded data over a desired time interval until the next batch of operational data can be ingested. Once the batch of data is ingested, the model parameters are adjusted to fit the observations. This general process repeats itself through the desired POR.

Two hindcast datasets have been used thus far to help characterize the sea states. The first of which is the **40**-year **C**orrected-**E**uropean Center for Medium-range Weather Forecasts (ECMWF) **R**e-**A**nalysis (C-ERA40) model (Caires and Sterl, 2005). The C-ERA40 model was generated at the Royal Dutch Meteorological Institute (KNMI), and provides SWH, 10 m wind speed, and average wave period at six-hour temporal resolution on a 1.5° latitude x 1.5° longitude grid. The POR extends from 1957-2001. However, the data from 1971-2001 are utilized because satellite and buoy data started to be used in the 1970s to provide better model validation. The second hindcast model is the National Center for Environmental Prediction's Optimal Interpolation (NCEP-OI) dataset (Reynolds et Al, 2002). This dataset is available online, and provides weekly mean SST on a 1° latitude x 1° longitude grid for the 1982-2006 POR.

Despite the appeal of containing data at favorable resolutions, hindcast data has drawbacks which must be considered. The favorable spatial and temporal resolutions of hindcast data can make it very easy to simply rely on hindcast data for generating climatologies. However, one cannot stress enough that model data is not actually observed, and the data must be validated and used in conjunction with whatever observational data is available in order to obtain the most robust and accurate climatology of a given sea state or atmospheric parameter. In addition, one must know any other nuances of the model being used. As an example, the C-ERA40 model is not valid for shallow water, and thus another data source needs to be used for coastal applications. The user of the model also must assume that conditions do not change on scales smaller than the temporal and spatial resolution provided by the model using valid physical arguments.

4. USES OF DATA SOURCES

The MSFC Natural Environments Branch utilizes the data sources described above to address the various questions given by the design and operations communities. A specific dataset is chosen based on data availability, the desired temporal and spatial resolution, and how well the dataset applies to the question being asked. The dataset to be used, along with the analysis method, is discussed with the customer prior to starting the analysis to make certain that the customer knows any and all assumptions which influence the result of the analysis being done. Once the analysis is completed, a data package is assembled containing the reason for the analysis and the study's methodology. Following review within the Branch, the data package is delivered to the customer, who utilizes the information provided to make vehicle design and recovery decisions.

Environments are provided to the engineering or operations communities for the desired parameter. Figure 2 shows an example of what can be provided. Here, SWH percentiles are shown for buoy 41009, which is located 37 km (20 nm) east of NASA's KSC. This type of plot could apply to a situation where the vehicle must abort shortly after launch, putting Orion and its crew just offshore. Rescue operations could use the SWH information ahead of time to discern how high the waves will likely be during a particular month.

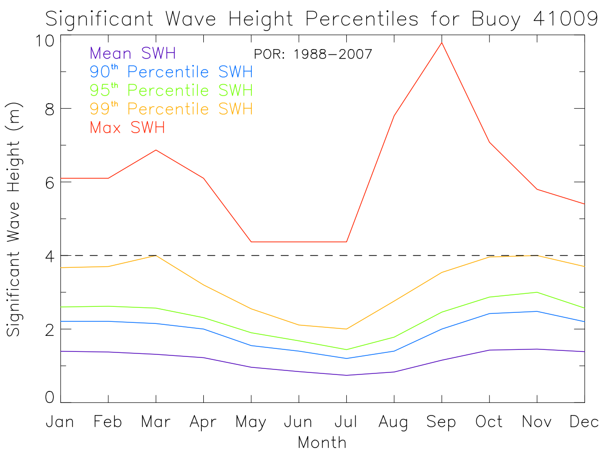

Figure 2: Percentiles of SWH at NDBC buoy 41009, located 37 km (20 nm) east of KSC. The dashed line represents a SWH of 4 m. The mean and maximum, along with the 90th, 95th, and 99th percentile SWH values for the month across the POR are plotted.

The environmental data can be tailored to answer specific questions provided by the Constellation design and operations communities. Figure 3 shows an example of this. In the figure, the probably of launch is shown assuming the SWH above a specified threshold (here, 3m, 4m, and 5m) cannot exist anywhere along the ascent ISS ground track. Customers can use this information, while knowing the assumptions of the analyses, to determine the overall probability of the vehicle launching during a particular month. In addition, the "knee in the curve" is typically obtained with analyses such as these, which identify to the customers the threshold ranges, if any, which are critical for mission success. In Figure 3, this "knee in the curve" can be seen across all three SWH thresholds, as the probability of launch due to SWH increases significantly if the threshold can be increased through the 3 m to 5 m range.

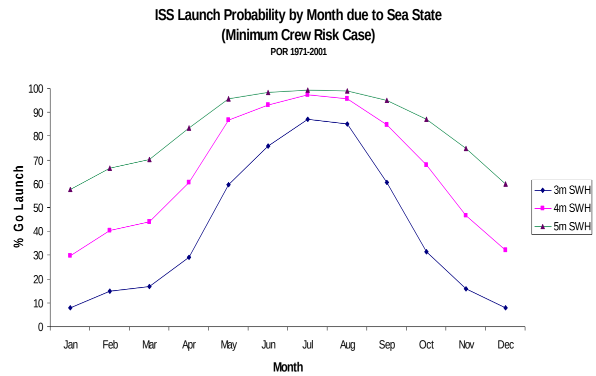

Figure 3: Monthly probabilities of Launch assuming SWH constraints of 3m, 4m, and 5m along the ISS ascent ground track using the C-ERA40 model data.

Multiple sea state parameters can also be investigated to provide conditional probabilities of encountering specified environments. As an example, Figure 4 shows the probability of encountering a specified average wave period within a given SWH range in a potential recovery region along the lunar ground track. Plots such as these can answer a question such as: "given an SWH of 4 m, what kind of wave periods can one expect within this region?" Customers can then use this information to decide whether or not they will be able to land and recover the vehicle along with its crew in the specified region based on the thresholds chosen. In addition to conditional probabilities, the sea state data can be configured to meet the customer's needs by addressing joint probabilities of two parameters occurring as well as incorporating climatological data into theoretical wave spectra.

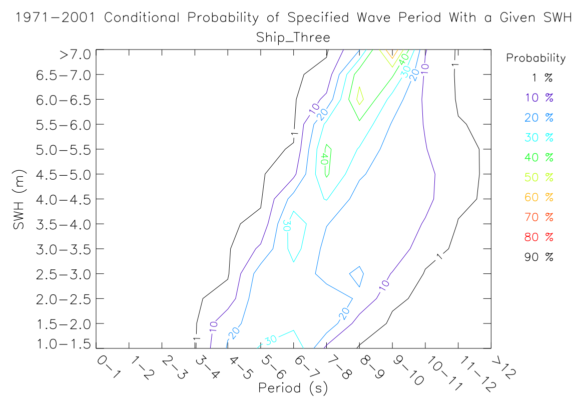

Figure 4: Conditional probabilities of a specified wave period occurring within given SWH ranges for a potential abort recovery zone along the lunar ground track. The probabilities are contoured at 1%, and from 10%-90% at 10% intervals. Data were obtained from the C-ERA40 model.

5. CONCLUSIONS

NASA's Constellation Program depends on the characterization of the sea states because the Ares / Orion vehicle must be able to withstand sea conditions during an oceanic landing during both nominal and abort landing modes. The MSFC Natural Environments Branch provides sea state information to the design and operations communities using both observational and hindcast data sources. Observational data sources, including *in-situ* measurements from buoys and ships as well as remotely-sensed measurements from satellites, have their own advantages and disadvantages. This paper presents the different data sources and their applicability to the Constellation Program as well as their respective advantages and disadvantages. The main disadvantage of the operational data sources is they do not provide the necessary temporal and / or spatial coverage for the Constellation Program.

The drawbacks of hindcast models and other data sources being used for a particular analysis, as well as the assumptions which influence the analysis, are communicated to the customer. To provide robust climatologies at the data-sparse locations of interest and to maintain an extensive POR, hindcast data from re-analysis models are utilized in conjunction with observational data sources. The hindcast data has been compared to observational data in both previous literature and within the Branch, and is utilized with the full understanding that it does not contain directly-measured data. With these different data sources, the right analysis technique and assumptions, and effective communication to the customer, the MSFC Natural Environments assists NASA's Constellation Program by providing invaluable sea state information to the design and operations communities.

6. LIST OF ACRONYMS

C-ERA40	40-year Corrected- European Centre for Medium-range Weather Forecasts Re-Analysis
ECMWF	European Centre for Medium-range Weather Forecasts
ISS	International Space Station
KSC	Kennedy Space Center
KNMI	Royal Dutch Meteorological Institute
MSFC	Marshall Space Flight Center
NASA	National Aeronautics and Space Administration
NCEP-OI	National Center for Environmental Prediction - Optimal Interpolation dataset
NDBC	National Data Buoy Center
POR	Period of Record
QC	Quality Control
SAR	Search and Rescue
SST	Sea Surface Temperature
SWH	Significant Wave Height
VOS	Voluntary Observing Ships

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