6.2 AN INTEGRATED APPROACH TO ANALYZE ASCENT ABORT GROUND TRACK SEA CONDITIONS FOR CREWED SPACE VEHICLES

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1. INTRODUCTION

This paper provides a methodology to support day-of-launch (DOL) sea condition assessments for space vehicles through examining both climatological variables and vehicle capabilities. Crewed vehicles launching from Kennedy Space Center (KSC) need to ensure that vehicles with abort-to-water capabilities can safely land in the ocean and that recovery personnel can reach and extract the crew in a timely manner if an abort occurs along the ascent abort ground track. As such, the programs impose limits to sea conditions, such as wave height and wind speed, to both vehicle and recovery capabilities.

The Marshall Space Flight Center Natural Environments Branch (NEB) determines the likelihood of violating the specified constraints along the ground track for mission planning and potential flight rule development. The NEB performs analyses of natural environment variables that apply to various parts of the vehicle (Burns, 2011), and NASA combines these analyses with other vehicle-specific assessments to estimate launch availability (Altino, et al., 2014).

The NEB has been assessing sea conditions for crewed missions utilizing the vehicle's ground track (i.e., the path along the Earth's surface over which the vehicle travels during ascent) and sea condition climatologies. However, the NEB has only considered geographical areas without regard to abort potential in these assessments. Not knowing the latter quantity leads to implementing an implied requirement to meet all criteria over the entire ground track, which then leads to potential over-conservatism in launch probability results. In addition, one would need to assume that the vehicle could land anywhere along the ground track when developing flight rules, which could lead to not launching when criteria are satisfied along the vast majority of the ground track. This paper describes how the NEB has attempted to bridge these gaps.

The NEB recently worked with colleagues at KSC and Johnson Space Center (JSC) to develop a methodology that combines the sea condition climatology with the probability of a given vehicle landing in specific areas along a ground track. This methodology requires the following inputs, upon which stakeholders from vehicle design, recovery, natural environments, etc., agree:

1. Sea condition climatology
2. Ascent ground track
3. Sea condition constraints
4. Vehicle abort probability
    - The probability of the vehicle aborting (hereafter P_{Abort})
    - The probability of landing at specified locations along the ground track, given an abort (hereafter P_{cond})
5. A criterion, provided by the vehicle program, of the risk tolerance for aborting into unsafe seas (hereafter R)

This paper provides a framework of how a vehicle program could implement the methodology presented herein, using examples of each of these inputs for illustrative purposes. Section 2 describes the sea condition climatology used in this paper, defines the example ground track and sea condition constraints, and presents results from assessing these criteria using the NEB's traditional methodology. Section 3 describes the abort probability inputs for two hypothetical vehicles, and introduces R. Section 4 provides the analysis methodology that integrates knowledge of sea conditions and vehicle abort capability. Section 5 presents analysis results from the examples defined, and Section 6 contains a summary. Vehicle programs could use analogous assessments to those presented in this paper to quantify the trade between R and launch probability. It is important to note here that vehicle programs are responsible for determining the risk of putting a crew into unsafe seas.

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2. TRADITIONAL INPUTS AND ANALYSIS RESULTS

This section contains the inputs that the NEB has used in traditional assessments of sea conditions, and presents an example of such an assessment. These same inputs are needed for the methodology presented in Section 4. Section 2.1 describes the sea condition climatology, Section 2.2 describes the ground track, Section 2.3 lists the sea condition constraints, and Section 2.4 presents an example traditional assessment. As stated in the introduction, quantities shown here constitute examples to be used for illustrative purposes only.

2.1 *Sea Condition Climatology*

This analysis requires a robust dataset containing the parameters of interest that characterize sea conditions on temporal and spatial scales that apply to potential vehicle landing areas. *In-situ* data sources, such as buoys, do not provide the necessary spatial coverage to characterize sea conditions across the ground track. Satellite measurements might not adequately characterize sea conditions along the entire ground track due to temporal and spatial data gaps existing for various reasons. Thus, it is recommended that one use a global reanalysis dataset for assessments of sea conditions along a ground track, which entails accepting and/or verifying the quality of reanalysis output (Barbré & Keller, 2008).

This paper utilizes the Interim European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis, or the ERA-Interim (Berrisford, et al., 2011). The NEB has downloaded and maintained an archive of several parameters for use in various sea condition analyses. Output exist on a 1.5° longitude by 1.5° latitude grid, at six-hour increments, from 1979-2018. Note that one could use data from any reanalysis dataset that provides the necessary sea condition outputs at the locations and timestamps of interest.

2.2 *Ground Track*

The ground track determines the area of the ocean on which one performs sea condition assessments. When using reanalysis datasets, the ground track determines the gridpoints that contain the data to be used. Launch inclination and launch site comprise two of the variables needed to define the ground track. This paper assumes a launch from KSC along a northerly inclination of 35°. Figure 1 displays this ground track plotted over the December mean (SWH) at each gridpoint.

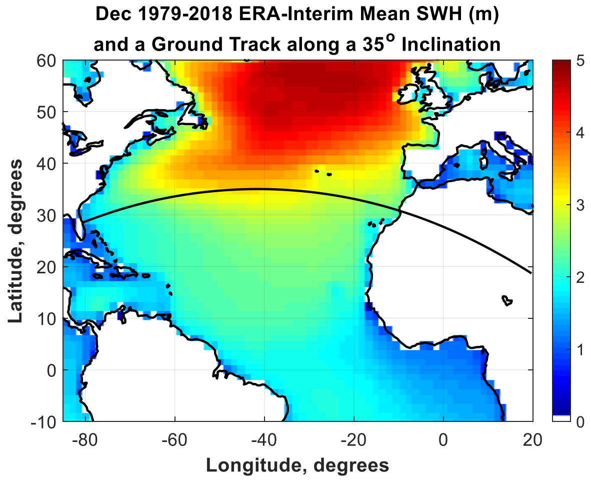

Figure 1: Mean SWH (m) at each gridpoint from the ERA-Interim reanalysis during December over the Atlantic Ocean. The black line denotes the ground track along a 35° inclination.

2.3 *Sea Condition Constraints*

Sea condition constraints are determined between all stakeholders involved. In a general sense, vehicle design and recovery comprise two of the entities that take the most interest in sea condition constraints. Constraints for vehicle design are nominally determined through assessments of vehicle tolerance to one or more environmental parameters. For example, a part on the vehicle may exceed its load limit in waves that exceed a certain height. Constraints for vehicle recovery depend on a myriad of logistical factors and recovery asset capabilities. For example, personnel may only be able to perform certain recovery operations in wind speeds under a specified threshold. Determining these constraints play a critical role in balancing crew and recovery safety with the desire to increase launch probability, which garners the interest of vehicle programs across multiple sub-organizations that are responsible for making pre-launch and operational decisions.

Once constraints are set, NEB assessments determine whether seas are “safe” or “unsafe” by assessing whether or not specific parameters violate given constraints. The example analysis provided in this paper applies the following sea condition constraints:

- SWH ≤ 3.0 m
- Wind speed at 10-m height ≤ 3.0 m
- Mean zero up-crossing wave period that is conditional to SWH

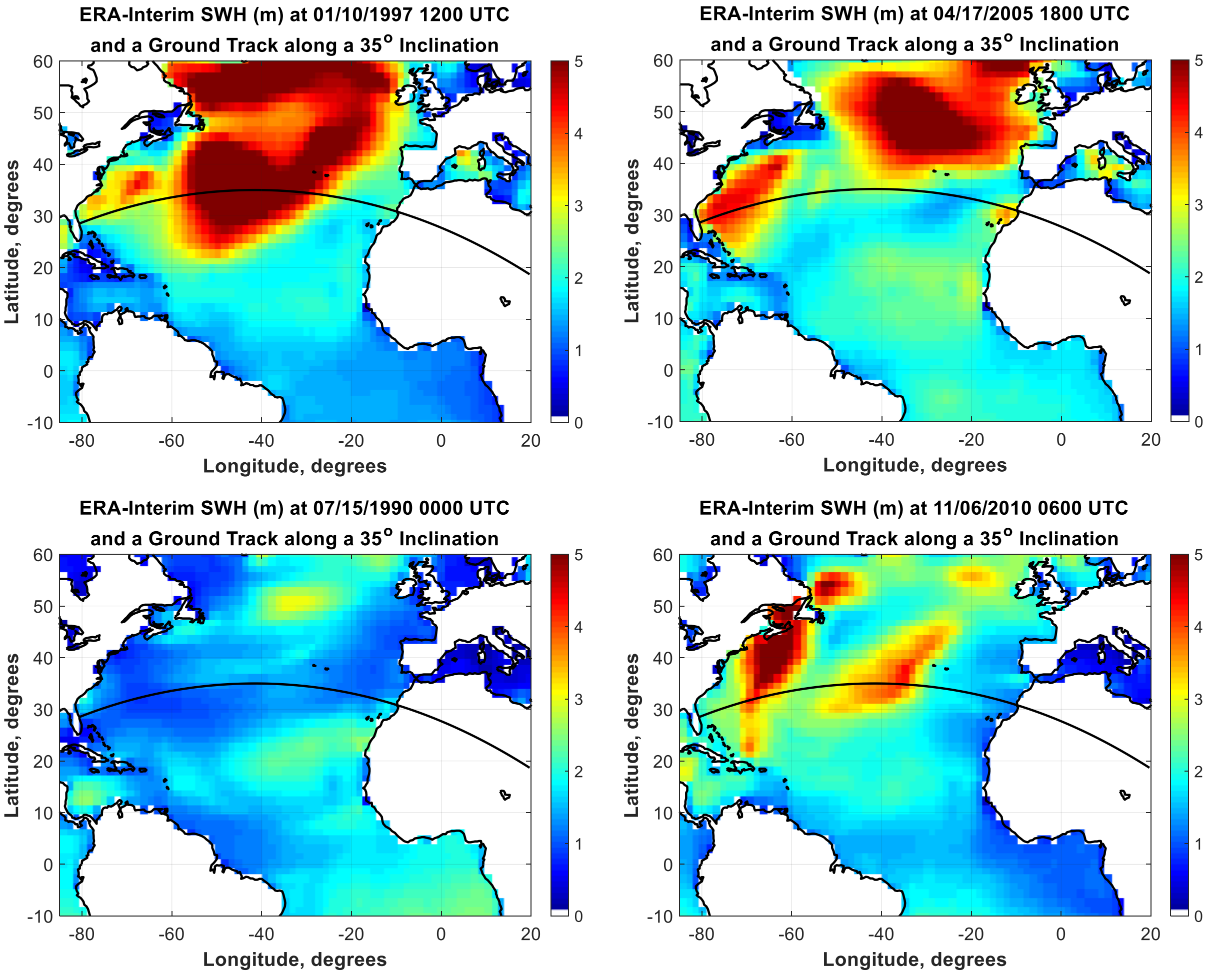

Figure 2: ERA-Interim SWH (m) at four individual days and times. The individual times are taken during arbitrary days within the Boreal winter (top-left), spring (top-right), summer (bottom-left), and autumn (bottom-right). The black line in each image denotes the ground track along a 35° inclination.

2.4 *Traditional Analysis Results*

Typically, both safe and unsafe sea conditions exist along the ground track at a given time, as Figure 2 illustrates. The weather patterns over the Boreal Atlantic tend to produce higher SWH during the winter months and lower SWH during the summer months, with more isolated areas of relatively high SWH forming during the transition months. Exceptions exist on individual days (e.g., tropical cyclones could cause high waves during the summer). In general, it is unlikely for the ground track to traverse regions of only safe seas or regions of only unsafe seas at a specified time.

The NEB's analysis approach prior to this paper generated results that could be difficult to justify for both mission planning and operational purposes. The overarching analysis methodology consists of determining the percent of timestamps in a climatology that pass or fail specified constraints (Burns, 2011). It thus becomes critical that one accurately determines what constitutes a pass or fail condition at an individual timestamp. Without knowledge of vehicle abort capabilities, the NEB assesses sea conditions assuming that the vehicle could land anywhere along the ground track. This philosophy imposes a requirement that all sea condition parameters of interest must pass their respective constraints for a given timestamp to be labeled a pass. Figure 3 shows the probability of not exceeding all constraints along the entire ground track. This probability, and the analogous results shown in Section 5, contributes to launch probability if a flight rule exists that states that none of the specified conditions can violate their constraint. While it is understood that launch probability accounts for other attributes both related and not related to natural environments, this paper equates launch probability in terms of only satisfying criteria related to sea conditions for brevity. The results shown in Figure 3 stem from accepting zero risk of landing in unsafe sea conditions anywhere along the ground track. Implementing this requirement limits launch probability, which does not exceed 10% from November through April and does not exceed 50% during any month.

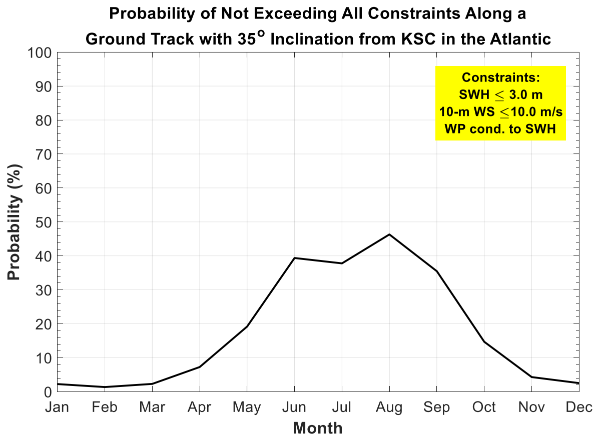

Figure 3: Probability of not exceeding all constraints along the entire ground track versus month.

Utilizing these results for mission planning would need to account for a significant degree of conservatism and logistical fallout. For example, if possible, a vehicle program might consider planning the majority of their launch attempts during the summer. In addition, one could raise a variety of questions to understand the risk of actually landing in unsafe seas better. For example, one might consider only examining a small geographical region along the ground track if said region were to contain the majority of instances of unsafe seas. However, implementing this approach could ignore other parts of the ground track that contain unsafe seas and, thus, could give decision-makers a risk assessment that does not account for the entire ground track.

In addition, developing a flight rule that states that safe sea conditions must exist along the entire ground track would likely be unreasonable for decision-makers to defend. As such, one might think to accept some risk of landing in unsafe seas. However, only examining geographical regions while not including the vehicle's abort capability presents similar limitations as those for mission planning. For example, implementing a flight rule that specifies that unsafe seas must not exist within a given geographical region ignores cases where unsafe seas exist just outside of said region, which could place decision-makers in an unnecessarily difficult position. In both mission and DOL decision-making, the actual risk of putting the crew into unsafe seas is unknown when only considering geographical areas.

3. ADDITIONAL ANALYSIS INPUTS

This paper incorporates two additional inputs that enable a more realistic and robust assessment of sea conditions for mission planning and operational decision-making. The first input consists of vehicle abort probabilities, and the second input is R, which again is a criterion, provided by the vehicle program, of the risk tolerance for aborting into unsafe seas.

3.1 *Vehicle Abort Probability*

The vehicle abort probability is characterized in a two-fold manner. These two quantities consist of the probability of abort (P_{Abort}) and the conditional probability of landing a specified downrange distance from the launch site, given that an abort has occurred (P_{cond}). Vehicle programs derive these quantities from design capabilities through probabilistic risk assessments conducted for specific vehicles, and provide said quantities to the NEB after vetting them through NASA Safety and Mission Assurance, if needed.

This paper utilizes abort probabilities from two hypothetical vehicles, which are denoted as Vehicle 1 and Vehicle 2. It is assumed that P_{Abort} = 1/100 for both vehicles, and Figure 4 shows P_{cond} for the two vehicles. P_{cond} for Vehicle 1 is uniform throughout the flight (up to 3,700 nmi downrange), which leads to retiring the cumulative risk linearly as a function of downrange distance. P_{cond} for Vehicle 2 is linear for much of the flight. However, it contains an instantaneous risk increase at 1,000 nmi, which simulates a significant event that increases the risk of abort at that time of flight.

Knowing the vehicle abort probability as a function of downrange distance characterizes the risk of landing in unsafe seas. Combining this input with the ground track produces locations along the ground track where the vehicle is more (or less) likely to land. Thus, the sea conditions that exist in regions in which the vehicle is more likely to abort influence launch probability calculations largely.

3.2 *Acceptable Risk Criterion*

The final input for the updated analysis methodology comprises of R, which quantifies the risk of the vehicle aborting into unsafe seas.

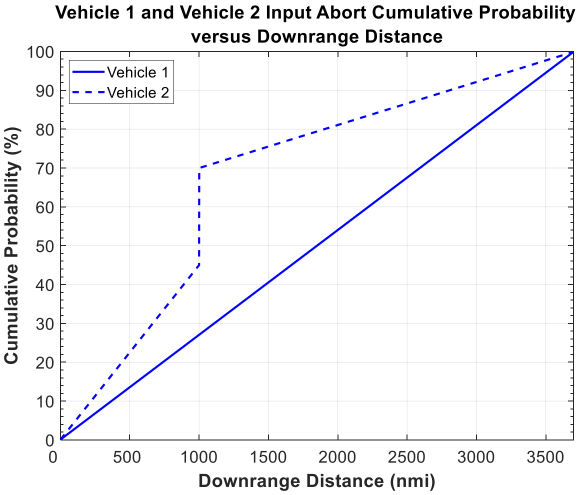

Figure 4: Cumulative probability of landing a specified distance from the launch site, given an abort, for Vehicle 1 (solid line) and Vehicle 2 (dashed line).

If the computed probability of aborting into unsafe seas exceeds R at a given timestamp, then the timestamp is marked as a fail. Conversely, the timestamp would be marked as a pass if the probability of aborting into unsafe seas does not exceed R. This paper examines results that stem from different, hypothetical, values of R, leading to the ultimate goal of describing a method to use climatological assessments to drive a determination of R that could be applied on DOL. Once again, vehicle programs would decide how to address the risk that said assessments characterize.

4. UPDATED ANALYSIS METHODOLOGY

This section provides the methodology to compute launch probability due to sea conditions through integrating vehicle abort capability. The process entails computing the probability of aborting into unsafe seas at each timestamp and then counting the number of timestamps where said probability does not exceed R.

The process utilizes the conditional probability formula

$$P_0 = P(A \cap B) = P(A|B) * P(B) \tag{1}$$

where P_0 is shorthand for $P(A \cap B)$. Independent events A and B are defined as:

- Event A denotes unsafe seas existing at a given location
- Event B comprises of the vehicle aborting

Event (A|B) denotes the vehicle landing in unsafe seas, given an abort. Thus P_{Abort} = P(B), and this paper defines P(A|B) as P_{unsafe}. Section 4.1 describes the method to compute P_{unsafe} using P_{cond} (Figure 4) and the sea condition climatology. Section 4.2 describes the comparison against R.

4.1 *Computing the Conditional Probability of Landing in Unsafe Seas*

This analysis computes the quantity P_{unsafe} as the percent of the ground track that contains unsafe seas, with weighting given according to the conditional downrange distance inputs. The ground track is overlaid on the reanalysis grid and is divided into segments, where reanalysis gridpoints surround an individual segment (Figure 5). If data from any of the surrounding reanalysis gridpoints violate their constraints, then the individual segment is flagged as containing unsafe sea conditions. In the example presented in Figure 5, the segment of interest is flagged as a fail if any of the surrounding gridpoints, marked in red, contain sea conditions that violate any constraint. The starting and ending downrange distances of the segment are also stored. This process is repeated for all segments along the ground track, which yields a set of starting and ending distances that either are flagged, or are not flagged, as having unsafe seas.

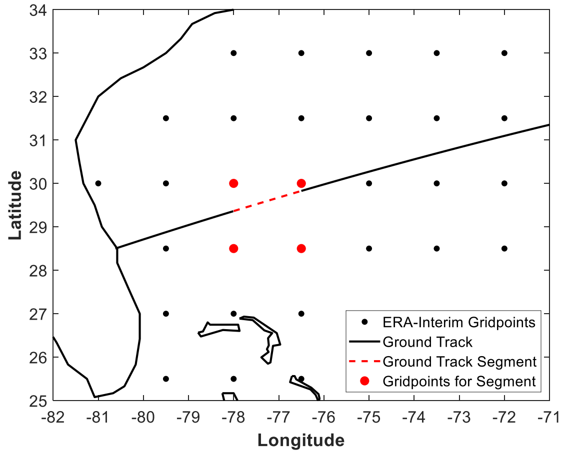

Figure 5: ERA-Interim gridpoints with the ground track overlaid. The dashed, red line denotes an arbitrary segment, and the larger, red gridpoints denote the gridpoints from which data are used to characterize sea conditions within the segment.

Using the worst case from the four surrounding gridpoints stems from previous formal and informal studies, performed by the author (Barbré, 2015), which found that the highest SWH from the four

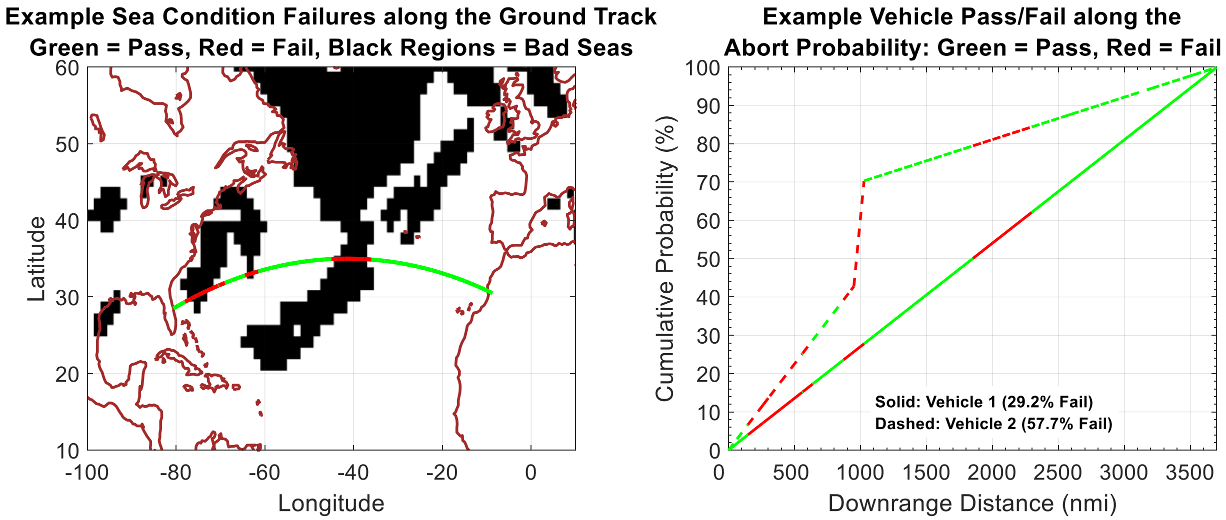

Figure 6: (Left) Map overlaying the ground track on sea conditions assessed at an arbitrary time. Black areas over the ocean denote unsafe seas. The green and red sections of the ground track denote segments that contain safe and unsafe seas, respectively. (Right) Abort probability versus downrange distance that is flagged according to the map on the left. The solid line denotes Vehicle 1 and the dashed line denotes Vehicle 2.

surrounding gridpoints compared better to buoy output versus using ERA-Interim output at the closest gridpoint. Additionally, applying this assumption preserves some conservatism to analysis results to account for any uncertainty in the ERA-Interim. This rationale addresses the need described in Barbré & Keller (2008) to handle any uncertainties with reanalysis output.

The quantity P_{unsafe} is obtained through summing the portions of P_{cond} that correspond to flagged segments. Figure 6 shows P_{unsafe} at an arbitrary timestamp for both Vehicle 1 and Vehicle 2. Vehicle 1 would have a 29.2% chance of landing in unsafe seas if it were to abort, but Vehicle 2 would have a 57.7% chance of experiencing the same phenomenon. Thus, for this example, decision-makers for Vehicle 2 would have to accept roughly twice the risk of landing in unsafe seas if the vehicle were to abort.

4.2 *Comparing Results to Accepted Risk*

The computed P_0 is compared to R to determine if the risk of aborting into unsafe seas is acceptable. P_0 is obtained at each timestamp through multiplying P_{unsafe} by P_{abort}. For the case presented in Figure 6, $P_0 = 1/342$ and $P_0 = 1/173$ for Vehicle 1 and Vehicle 2, respectively. Thus, implementing any R at least these quantities would yield acceptable sea conditions at this time.

For these examples, Vehicle 2 also needs roughly twice the risk of aborting into unsafe seas to declare acceptable seas because both vehicles have the same P_{Abort}. If Vehicle 2 were to have $P_{Abort} = 1/200$, then its P_0 would be 1/347. Thus, the total probability of aborting into unsafe seas would be very close to that of Vehicle 1, even though the chance of landing in unsafe seas given an abort would remain roughly twice that of Vehicle 1.

Counting the number of instances where $P_0 \leq R$ determines launch probability. This quantity P is computed as

$$P = \frac{N_{P_0 \leq R}}{N} \qquad (2)$$

Where N denotes the number of reports in the sea condition climatology during an individual month.

5. EXAMPLE ANALYSIS RESULTS

Analysis results, which are analogous to launch probability, comprise the probability of acceptable sea conditions versus month and R. Figure 7 shows Vehicle 1 launch probability for R = 1/250, 1/500, 1/1000, and 1/2000. As expected, accepting a higher R (i.e., higher risk tolerance of aborting into unsafe seas) increases launch probability. For example during April, R = 1/250 and R = 1/2000 yield launch probabilities of roughly 70% and 10%, respectively. The variation by month still exists, but the launch probability is now a variable that depends on R.

Comparing these results to results from the NEB's traditional methodology (Figure 3) shows little improvement during winter, except for high R,

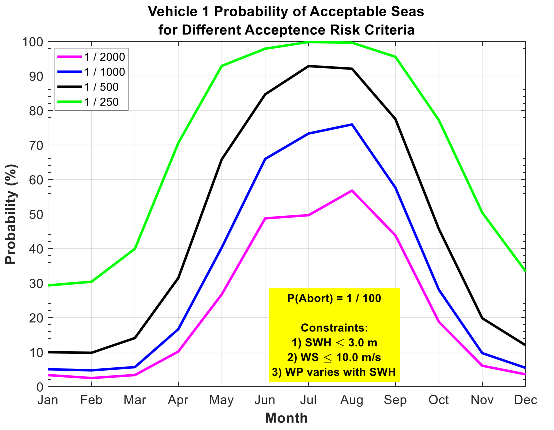

Figure 7: Probability of acceptable seas versus month for Vehicle 1 and different values of R.

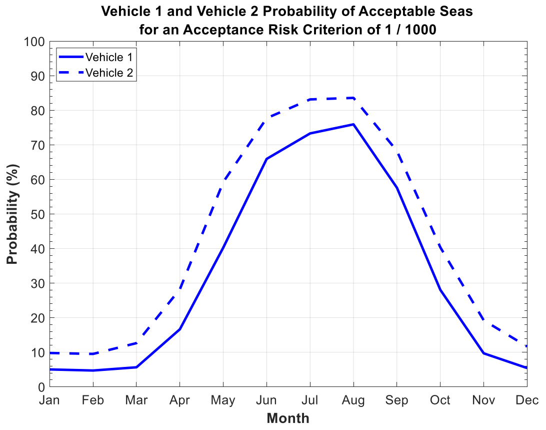

Figure 8: Probability of acceptable seas versus month for Vehicle 1 (solid line) and Vehicle 2 (dashed line) for R = 1/1000.

and shows more notable improvement during summer. Launch probability remains at or below 20% from November through March for all R shown except for R = 1/250. However, implementing R > 1/2000 would yield increases in launch probability by at least roughly 20% from June through August.

One could also utilize this methodology to compare results for different vehicles. Figure 8 shows launch probability versus month for both example vehicles at R = 1/1000. Examining results in this manner reveals that accepting a 1/1000 risk of aborting into unsafe seas yields roughly a 5-10% increase in launch probability for Vehicle 2. This result is opposite of the result presented in Figure 6, where Vehicle 2 had a greater chance of aborting into unsafe seas at a given time. However, this attribute stems from a small area of unsafe seas existing within a geographical region corresponding to the significant increase in Vehicle 2's abort risk near 1,000 nmi downrange. The results in Figure 8 show that the scenario presented in Figure 6 occurs rarely, and that Vehicle 2 actually has a greater probability of launch than Vehicle 1 if one were to accept R = 1/1000 for both vehicles.

6. SUMMARY

This paper documents a methodology that vehicle programs can implement to quantify launch probability as a function of sea conditions, vehicle abort capability, and accepted risk of landing in unsafe seas. The inputs needed to implement this methodology comprise of

1. Sea condition climatology
2. Ascent ground track
3. Sea condition constraints
4. Vehicle abort probability
    - ○ The probability of the vehicle aborting, P_{Abort}
    - ○ The probability of landing at specified locations along the ground track, given an abort, P_{cond}
5. A criterion, provided by the vehicle program, of the risk tolerance for aborting into unsafe seas, R

First, the quantity P_{unsafe}, which denotes the percent of the ground track that contains unsafe seas given an abort, is computed using the sea condition climatology and P_{cond}. Next, P_{unsafe} is multiplied by P_{Abort} to obtain P_0, which is the probability of aborting into unsafe seas at a given time. Then, the number of instances where P_0 does not exceed R is tallied. Last, the percentage of this tally is displayed for each month.

For mission planning, climatological assessments are used to determine the appropriate R to implement on DOL. The paper presents hypothetical examples, but one should note that the analysis results presented in Section 5 contain more robust applications than the results shown in Section 3. For example, accepting a low R does not produce a significant increase in launch probability during the winter months, but one could link analysis results to a quantified risk tolerance of which the vehicle program agrees to accept. This risk also includes the probability of abort, and thus can be utilized and tracked throughout vehicle design and mission planning. Assessing only geographical areas, without regard to vehicle abort capability, does not allow for such a quantification of this risk.

This method also allows vehicle programs to develop flight rules using a given R. One would replace the sea condition climatology with a gridded forecast dataset, and implement the process defined in Section 4. Also, P_{unsafe} may be the only quantity needed. For example, one could develop a flight rule saying that launch would not occur if P_{unsafe} exceeded a given percentage of the ground track. Implementing this methodology operationally produces a quantified risk of aborting into unsafe seas at launch time while considering the entire ground track. Vehicle programs can then compare this risk to a pre-determined, quantified, criterion; which would provide high levels of confidence in understanding the risk of aborting into unsafe seas while maximizing launch probability.

7. ACKNOWLEDGMENTS

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