6.4 TERRESTRIAL ENVIRONMENT (CLIMATIC) CRITERIA HANDBOOK FOR USE IN AEROSPACE VEHICLE DEVELOPMENT

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1. INTRODUCTION

Aerospace Meteorology provides the identification of that aspect of meteorology that is concerned with the definition and modeling of atmospheric parameters for use in aerospace vehicle development, mission planning and operational capability assessments. One of the principal sources of this information is the NASA-HDBK-1001 "Terrestrial Environment (Climatic) Criteria Handbook for Use in Aerospace Vehicle Development". This handbook (Anon, 2000) was approved by the NASA Chief Engineer in 2000 as a 'NASA Preferred Technical Standard'. Its technical contents were based on natural environment statistics/models and criteria developed mostly in the early 1990's (Johnson, 1993). A task was approved to completely update the handbook to reflect the current state-of-the-art in the various terrestrial environment climatic areas.

This handbook originally goes back to the early 1960's and has been periodically updated as a NASA Technical Memorandum (TM). The reader is also referred to the references of Anon (2004), Johnson (2002), Johnson (2003), Pearson (1996), Vaughan (1985) and Vaughan (1999) for a better insight into developing, modeling, and interpretation of terrestrial environment parameters for application to aerospace vehicle engineering problems. The SLaTS (Space Launch and Transportation Systems) document by Larson (pending), along with the wind related documents of Adelfang (1999) and Smith (1998) are particularly useful in describing the various atmospheric and wind model applications.

The structure of the handbook, along with the fourteen technical sections, is given in Table 1. Status on the update is presented in this paper along with a few key examples. This handbook is prepared for the aerospace community, program managers and design engineers as a source document for required natural terrestrial environment inputs for use in aerospace vehicle mission planning, design and trade studies.

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2. BACKGROUND

This handbook revision will contain new and updated material in most sections. Specifically, aerospace vehicle design guidelines are provided and presented by sections as presented in Table 1. The last section in this handbook includes information on physical constants and English/Metric unit conversion factors.

In general, the handbook does not specify how the designer should use the data in regard to a specific aerospace vehicle design. Such specifications may be established only through analysis and study of a particular design problem. Although of operational significance, descriptions of some atmospheric conditions have been omitted since they are not of direct concern for an aerospace vehicle system's design, the primary emphasis of this document. Induced environments (vehicle caused) may be more critical than the natural environment for certain vehicle operational situations. In some cases the combination of natural and induced environments will be more severe than either environment alone. Induced environments are considered in other aerospace vehicle design criteria documents, which should be consulted for such information.

The natural environment criteria guidelines presented in the handbook were formulated based on discussions with and requests from engineers involved in aerospace vehicle development and operations. Therefore, they represent responses to actual engineering problems and lessons learned. The handbook is not just a general compilation of environmental data. The NASA Centers, various other Government agencies, and their associated contractors responsible for the design, mission planning, and operational studies use this document extensively. The Glossary of Climate and Meteorology, published by the American Meteorological Society, 45 Beacon Street, Boston, MA

02108, should be consulted for the definition of environment terms not otherwise defined in this document.

2.1 Engineering Importance

Atmospheric phenomena play a significant role in the design and operation of aerospace vehicles and in the integrity of the associated aerospace systems, elements and payloads. It is important to recognize the need to define the terrestrial environment design requirements very early in the design and development cycle of any aerospace vehicle; see Ryan (1996). This is especially true for a new configuration. Using the desired operational capabilities and flight profiles for the vehicle, specific definitions of the terrestrial environment can be provided which, if the aerospace vehicle is designed to accommodate, will ensure the desired operational capability within the defined design risk level. It is very important that those responsible for the terrestrial environment definitions for design of an aerospace vehicle have a close working relationship with program management and design engineers. This will ensure that the desired operational capabilities are reflected in the terrestrial environment requirements specified for design of the vehicle.

An aerospace vehicle's response to terrestrial environment design criteria must be carefully evaluated to ensure an acceptable design relative to desired operational requirements. The choice of criteria depends upon the specific launch and landing location(s), vehicle configuration, and the expected mission(s). Vehicle design, operation, and flight procedures can be separated into particular categories for proper assessment of environmental influences and impact upon the life history of each vehicle and all associated systems. These include categories such as:

(1) purpose and concept of the vehicle
(2) preliminary engineering design
(3) structural design
(4) control system design
(5) flight mechanics, orbital mechanics and performance (trajectory shaping)
(6) optimization of design limits regarding the various natural environmental factors
(7) final assessment of natural environmental capability for launch and flight operations

Another important requirement that must be recognized is the necessity for having a coordinated and consistent set of terrestrial environment requirements for use in a new aerospace vehicle's design and development. This is particularly important where diverse groups are involved in the development, and is of utmost importance for any international endeavor. A "central control point" focused on definition and interpretation of the terrestrial environment inputs is critical to the successful design and operation of any new aerospace vehicle. Without this control, different terrestrial environment values or models can be used with costly results, both in terms of money, time, and vehicle performance. This "central control point" should include responsibility for mission analysis, test support requirements, flight evaluation and operational support relative to terrestrial environment requirements.

During the early stages of a new aerospace vehicle's design and development, trade-off studies to establish sensitivities of various terrestrial environment-forcing functions are important. Feedback from these studies is key to establishing the necessary terrestrial environment inputs for the vehicle's final design requirements, including a single source (central control point) responsible for the preliminary design trade-off study terrestrial environment inputs and their interpretation is important. This will preclude a multitude of problems in the final design and development process. This will also enable terrestrial environment requirements for the development of an aerospace vehicle to be established with a minimum amount of communication problems and misunderstanding of design issues.

The close association between the design and test engineering groups and those responsible for the terrestrial environment inputs is key to the success of the vehicle's development process. This procedure has been followed in many NASA aerospace vehicle developments and is of particular importance for any new aerospace vehicle. Figure 1 illustrates the necessary interactions relative to terrestrial environment definition and engineering application. Feedback is critical to the process and ability to produce a viable vehicle design and operational capability.

Finally, although often not considered to be significant, it is of major importance that all new aerospace vehicle design review meetings include a representative from the terrestrial environment group (central control point) assigned to support the program. This will ensure good understanding of design requirements and timely opportunity to incorporate terrestrial environment inputs and interpretations, which are tailored to the desired operational objectives, into the design process. It is also necessary that any proposed deviations from the specified terrestrial environment requirements, including those used in preliminary design trade-off studies, be approved by the responsible terrestrial environment "central control point" to ensure that all program elements are using the same baseline inputs. This will help the program manager understand the operational impact of any change in terrestrial environment requirements before implementation into the design. Gross errors and deficiencies in design can result from use of different inputs selected from various diverse sources by those involved in design and other performance studies.

2.2 Terrestrial Environment Issues

For terrestrial environment extremes, there is no known physical upper or lower bound except for certain environmental conditions. For example, wind speed does have a strict physical lower bound of zero. Essentially all observed extreme conditions have a finite probability of being exceeded. Consequently, terrestrial environment extremes for design must be accepted with the knowledge that there is some risk of the values being exceeded. The measurement of many environmental parameters is not as accurate as desired. In some cases, the use of theoretical model estimates for design values are believed to be more representative for design use than those indicated by empirical distributions from short periods of record. Therefore, theoretical values have been given considerable weight in selecting extreme values for some parameters, i.e., the peak surface winds. Criteria guidelines are presented in the handbook for various percentiles based on available data samples. Caution should be exercised in the interpretation of these percentiles in aerospace vehicle studies to ensure consistency with physical reality, and the specific design and operational problems of concern.

Aerospace vehicles are not normally designed for launch and flight in severe weather conditions such as hurricanes, thunderstorms, ice storms, and squalls. Environmental parameters associated with severe weather that may be hazardous to aerospace vehicles include strong ground and in-flight winds, strong wind shears and gusts, turbulence, icing conditions, and electrical activity. Terrestrial environment guidelines usually provide information relative to severe weather characteristics that should be included in design requirements and specifications if required to meet the program mission requirements.

Knowledge of the terrestrial environment is also necessary for establishing test requirements for aerospace vehicles and designing associated support equipment. Such data are required to define the fabrication, storage, transportation, test, preflight design condition and should be considered for both the whole vehicle system and the components which make up the system. This is one of the uses of guideline data on terrestrial environment conditions for the various major geographic locations applicable to the design of a new vehicle and associated supporting equipment.

The group having the responsibility and authority "central control point" for terrestrial environment design requirement definition and interpretation must also be in a position to pursue applied research studies and engineering assessments relative to input updates. This is necessary to ensure accurate and timely terrestrial environment definitions that are tailored to the program's needs. Design engineers and program management that assume they can simply draw on the vast statistical data bases and numerous models of the terrestrial environment currently available in the literature, without interpretation and tailoring to specific vehicle design needs, will discover that this can prove to be a major deterrent to the successful development and operation of an aerospace vehicle.

Although a vehicle design should accommodate expected operational environment conditions, it is neither economically or technically feasible to design an aerospace vehicle to withstand all terrestrial environment extremes. For this reason, consideration should be given to the protection of vehicles from some extremes. This can be achieved by use of support equipment and specialized forecast personnel to advise on the expected occurrence of critical terrestrial environment conditions. The services of specialized forecast personnel and atmospheric measurements may be very economical in comparison with more expensive vehicle designs that would be necessary to cope with all terrestrial environment possibilities.

Although the terrestrial environment is the major environmental driver for an aerospace vehicle's design and is the focus of this document, the natural environment above 90 km must also be considered in the design of aerospace vehicles. The orbital phase of an aerospace vehicle includes exposure to space environment such as atomic oxygen, on-orbit atmospheric density, ionizing radiation, plasma, magnetic fields, meteoroids, etc., plus a few man made environments such as orbital debris. Specific aerospace vehicle space environments design requirements are normally also specified in the appropriate aerospace vehicle design criteria documentation.

Good engineering judgment must be exercised in the application of terrestrial environment inputs to an aerospace vehicle design analysis. Consideration must be given to the overall vehicle mission and system performance requirements. Knowledge is still lacking on the relationship between some of the terrestrial environment parameters that are required as inputs to the design of aerospace vehicles. Also, interrelationships between vehicle parameters and terrestrial environment variables cannot always be clearly defined. Therefore, a close working relationship and team philosophy must exist between the design and operational engineer and the respective organization's terrestrial environment specialists.

2.3 Vehicle and Environment Areas of Concern

As noted, it is important that the need for definition of the ground, ascent, on-orbit, and descent aerospace vehicle operational terrestrial environments be recognized early in the design and development phase of the vehicle program. Engineering technology is constantly changing. In some cases the current trends in engineering design have increased vehicle susceptibility to terrestrial environment factors. Based on past experience, the earlier the terrestrial environment specialists "central control point" become involved in the design process, the less the potential for negative environmental impacts on the program downstream, through redesign, operational work-around, etc.

Table 2 provides a reference guide for the terrestrial environment specialist, program management and design engineers on the development team for a new aerospace vehicle program. This information summarizes potential terrestrial environment areas of engineering concern when first surveying a vehicle program. As can be noted from this table, terrestrial environment phenomena may significantly affect multiple areas of an aerospace vehicle's design and thus operational capabilities, including areas involving structure, control, trajectory shaping (performance), heating, takeoff and landing capabilities, materials, etc. A breakout of typical terrestrial environment concerns with respect to both engineering systems and mission phase is shown in the matrix.

3. SELECTED EXAMPLES

3.1 Winds Aloft Example

The definition of ground winds and winds aloft plays a key role as inputs into the design and development of an aerospace vehicle or associated system(s). Although the value of the synthetic Vector Wind Profile (VWP) Model was presented in both Anon (2000) and Johnson (1993), emphasis was also given to synthetic scalar wind profile models and their statistics. Since those publications, many VWP model improvements have been put in place; see Adelfang (1999) and Smith (1998). Detailed information on the VWP will be presented in the revised handbook as the recommended in-flight wind model. A VWP example is presented in Figure 2 in which the 12 KSC, 0-27 km altitude VW profiles for February, with a reference altitude of 12 km, are used as inputs into an engineering vehicle trajectory simulation program which outputs the two aerodynamic load indicators ($Q\alpha$ and $Q\beta$) as a variable dispersion at 12 km altitude. As can be noted, the 12 resultant load indicators encompass all the 1800 measured wind input load results, as well as the 95% vector ellipse. Engineering design users do not need to input thousands of wind profiles, but only 12, if the synthetic VWP model is used.

3.2 Model Atmospheres - GRAM Example

The initial development work relative to the NASA-MSFC Global Reference Atmospheric Model (GRAM) occurred at Marshall Space Flight Center (MSFC) over 30 years ago as the 4-D Global Atmospheric Model. The GRAM has been improved periodically. GRAM-99, described in Justus (1999), provides complete geographical and altitude coverage (up to 2500 km) for each month of the year. Mean values of atmospheric temperature, pressure and density along with winds are available from GRAM-99 plus the variability (sigma's) about the monthly mean. An atmospheric vertical profile above any Global site or values along any inputted aerospace vehicle flight trajectory can be obtained. Figure 3 illustrates the various GRAM-99 databases versus altitude that are used in the model.

The newest features that the GRAM-99 model incorporates are water vapor and 11 other atmospheric constituents (O_3, N_2O, CO, CH_4, CO_2, N_2, O_2, O, A, He and H). A variable-scale perturbation model provides both large-scale (wave) and small-scale (stochastic) deviations from mean values for thermodynamic variables and horizontal and vertical wind components. The small-scale perturbation model includes improvements in representing intermittency ("patchiness"). A major new feature of GRAM-99 is an option to substitute data from the thirteen Range Reference Atmospheres (RRA) for the conventional GRAM climatology when a trajectory passes sufficiently near these Northern Hemisphere RRA sites (Ascension Island, Barking Sands, Cape Canaveral, Dugway, Edwards AFB, Eglin AFB, Vandenberg AFB, Point Mugu, Kwajalein, Taquac Guam, Wallops Island, White Sands, and Kodiak Island). See Anon (2004).

Figures 4 and 5 present a GRAM-99 example involving a computation of mean and extreme atmospheric density values along a typical vehicle re-entry trajectory into Edwards AFB in January. Figure 4 presents this ground-track, relative to the vehicle's trajectory, with associated time and altitude values. Figure 5 presents two resultant GRAM-99 atmospheric density computations (as a ratio of the US76 Standard Atmosphere density). The left figure shows the trajectory path with average January density values (all versus height and longitude). The right figure presents the same trajectory verses density ratio (on ordinate) and longitude (on abscissa). Here the GRAM-99 mean density is presented along with the plus and minus 2-sigma values. Also shown is one example of the monte-carlo realistic density profile along the trajectory that the GRAM-99 produces.

3.3 Sea State Example

Knowledge of sea state characteristics and probabilities are important to aerospace vehicle water entry elements design and trade studies. This information is needed for use in the development of detailed design requirements and specifications, such as for entry, afloat, recovery, secure, tow back, and other operational analyses. Sea state is determined by the mean wind speed, the fetch (the distance over which it blows), and the duration of wind over open water.

The availability within the last decade of data from satellites such as GEOSAT, TOPEX/Poseidon, ERS-1, and ERS-2 coupled with computer model data has made possible the means to provide selected sea state characteristics and probabilities on essentially a global basis in a way that was previously impossible with only Land/Sea-based wind and wave measurements. Using 10 years of satellite altimeter observations of significant wave height and wind speed together with numerical model values for peak wave period, mean wave period, mean wave direction, and mean wind direction a global wind/wave atlas has been developed and recorded on CD ROM; Young (2003). Using commercially available MATLAB software, the CD ROM can be utilized to calculate and plot historical sea state characteristics such as mean monthly wave height, mean monthly wind speed, wave height exceedance, wind speed exceedance, mean monthly spectral peak period, mean monthly spectral mean period, spectral peak period exceedance, spectral mean period exceedance, mean monthly wave duration, mean monthly wind direction, and extreme wave heights for nearly any designated latitude and longitude ocean location. It should be noted that this CD ROM uses longitudes measured East rather than West.

Figure 6 is a global contour plot example of mean monthly wave height in meters for the month of January. Figure 7 is another global plot example of mean wave direction for the month of August with arrows indicating wave direction of travel. These two figures are typical examples of the output available from the Sea State Atlas/CD ROM; Young (1999).

3.4 Tornado Example

The SAT-3.0 tornado program from VorTek (see Johnson (1996) and Tatom (2003)) provided the update to the tornado statistics in the handbooks section 12. The SAT-3.0 period of record extended from 1950 through 2001 and was used in the update. Table 3 presents various tornado statistics for different sites of interest to NASA activities. The Annual Coverage Fraction (ACF) is an areal tornado statistic in which the total area encompassed by tornado tracks is calculated and used within any circular area of interest. Over this 52-year POR, Houston TX ranked number 2 in the nation behind Oklahoma City OK in total number of tornadoes per 1000 sq miles, for both a 20- and a 40-mile radius. Although Johnson Space Center (JSC) experienced far more tornadoes (310 total), within a circular radius (equivalent to a 1^{o} latitude-longitude square) than did Marshall Space Flight Center (134 total). It turns out that the amount of ground area engulfed by the stronger and larger Marshall tornadoes (ACF = 8.1×10^{-4}) was much more than that experienced at Johnson (ACF = 3.1×10^{-4}) by the weaker, mainly 'touch-down' type tornadoes that occurred at JSC. The 10 year tornado probabilities for a 1 square mile area at these locations are also given in Table 3.

Figure 8 presents as an example a map of all the tornado tracks and touchdowns (with dates and intensity) that have occurred within 20 miles of MSFC over the POR of 1950 through 2001. Figure 9 shows an example of a complete annual tornado probability map for the State of Florida with Kennedy Space Center (KSC) being close to the center of maximum tornado probability.

4. SUMMARY REMARKS

Given that all aerospace vehicles must operate within the terrestrial environment for some part, if not all, of their mission, the importance of having an adequate and controlled terrestrial environment definition and interpretation for design use is evident. The Terrestrial Environment (Climatic) Criteria Handbook for Use in Aerospace Vehicle Development (NASA–HDBK-1001) is intended to serve this purpose as a source document from which terrestrial environment design requirements can be derived relative to the intended operational capability desired for a new aerospace vehicle. This handbook can be obtained and downloaded at: http://standards.nasa.gov.

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Table 1. Sectional Layout of Terrestrial Environment (Climatic) Criteria Handbook for Use in Aerospace Vehicle Development (NASA-HDBK-1001)

Section	Title
1	Introduction
2	Winds
3	Atmospheric Thermodynamic Properties and Models
4	Solar and Thermal Radiation
5	U.S. and World Surface Extremes
6	Humidity
7	Precipitation Fog and Icing
8	Cloud Phenomena and Cloud Cover Models
9	Atmospheric Electricity
10	Atmospheric Constituents
11	Aerospace Vehicle Exhaust and Toxic Chemical Release
12	Occurrence of Tornadoes and Hurricanes
13	Geologic Hazards
14	Sea State
15	Mission Analysis, Prelaunch Monitoring, and Flight Evaluation
16	Conversion Units

Table 2. Key Terrestrial Environment Parameters Needed versus Engineering Systems (X) and Mission Phase (P).

X	Terrestrial Environment Parameter											P
Launch Vehicle Systems (Sub-)	Winds & Gusts	Atmosphric Thermodyn	Atmosph Constit	Solar/ Thermal Radiation	Atmosph Electricy	Clouds & Fog	Humidity	Precip or Hail	Sea State	Severe Weather	Geologic Hazzards	**Mission Phase**
System	X P	X P	X P	X P	X P	X P	X P	X P	X P	X P	X	Mission Analysis
Propulsion/ Engine Sizing	X	X P	P		X		X P			X		Manufactur-ing
Structures/ Airframe	X P	X P		X	X P		P	X P	X	X P	P	Testing
Performance/ Trajectory/G&N	X P	X P	P	P	X P	P	P	P	P	P	P	Transport & Ground Hdl
Aerodynamics	X P	X P	P	P	P		P	P	P	P		Rollout/On-pad
Thermal Loads/ Aerodynamic Heat	X P	X P	P	X P	P	P	P	P	P	P		Pre-launch DOL cnt dn
Control	X P	X P	P	P	X P	P	P	P		X P		Liftoff/ Ascent
Loads	X P	X P			P	P		P	X P	X P		Stages Recvry
Avionics	P	P	X	X	X P	P	X	P		X P		Flight
Materials	X	X P	X P	X P	X		X	X	X	X		Orbital
Electrical Power	P	P	X		X P	X		X P		P		Descent
Optics	P	X P	X P	X	P	X P	P	X P	P	P		Landing
Thermal Control	P	X P	P	X P	P		P	X P	P	P		Post-land
Telemetry, Tracking & Communication	P	X P	X P	P	X P	X P	P	X P	P	X P	P	Ferry/ Transport
	P				P		P	P		P	P	Facil/spt Eq
	P	P	P		P		P	P			P	Refurbishmt
Mission Operations	X P	X P	X P	X P	X P	X	X P	X P	X	X P	X P	Storage

Table 3. Tornado Statistics for Stations Specified, 1950-2001

Station:	Number of Tornadoes in Circular Region	Mean No./Year in Circular Region	Area* (A_2) of Circular Region km^2	(mi^2)	Radius of Circular Region km	(mi)	Annual Coverage Fraction (ACF) (yr^{-1})	Recurrence Interval 1/ACF (yr)	Average Tornado Size $\bar{A}_T$ (mi^2)	10 year Tornado Prob for A=2.59km^2 or (1 mi^2)
O Marshall Space Flight Center	134	2.58	10,179	(3,930)	56.89	(35.36)	**$8.069 \cdot 10^{-4}$**	**1,239**	**1.230**	**6.54×10^{-2}**
O Kennedy Space Center	124	2.38	10,839	(4,185)	58.73	(36.50)	$7.498 \cdot 10^{-5}$	13,337	0.132	5.67×10^{-3}
O Vandenberg AFB	3	0.0577	10,179	(3,930)	56.89	(35.36)	$4.827 \cdot 10^{-10}$	$2.071 \cdot 10^{9}$	3.29×10^{-5}	1.47×10^{-4}
O Edwards AFB	8	0.154	10,179	(3,930)	56.89	(35.36)	$1.851 \cdot 10^{-8}$	$5.402 \cdot 10^{7}$	4.73×10^{-4}	3.92×10^{-4}
O New Orleans	101	1.94	10,645	(4,110)	58.20	(36.17)	$3.627 \cdot 10^{-5}$	27,571	7.67×10^{-2}	4.71×10^{-3}
O NSTL	196	3.77	10,645	(4,110)	58.20	(36.17)	$7.150 \cdot 10^{-4}$	1,399	0.780	9.13×10^{-3}
O Johnson Space Center	**310**	**5.96**	10,736	(4,145)	58.44	(36.32)	$3.121 \cdot 10^{-4}$	3,204	0.217	1.43×10^{-2}
O White Sands MR	7	0.135	10,412	(4,020)	57.55	(35.77)	$1.017 \cdot 10^{-6}$	$9.833 \cdot 10^{5}$	3.04×10^{-2}	3.36×10^{-4}

*** Area of circular region equal to area of 1° square.**
Note: Bold type indicates most extreme tornado statistics.

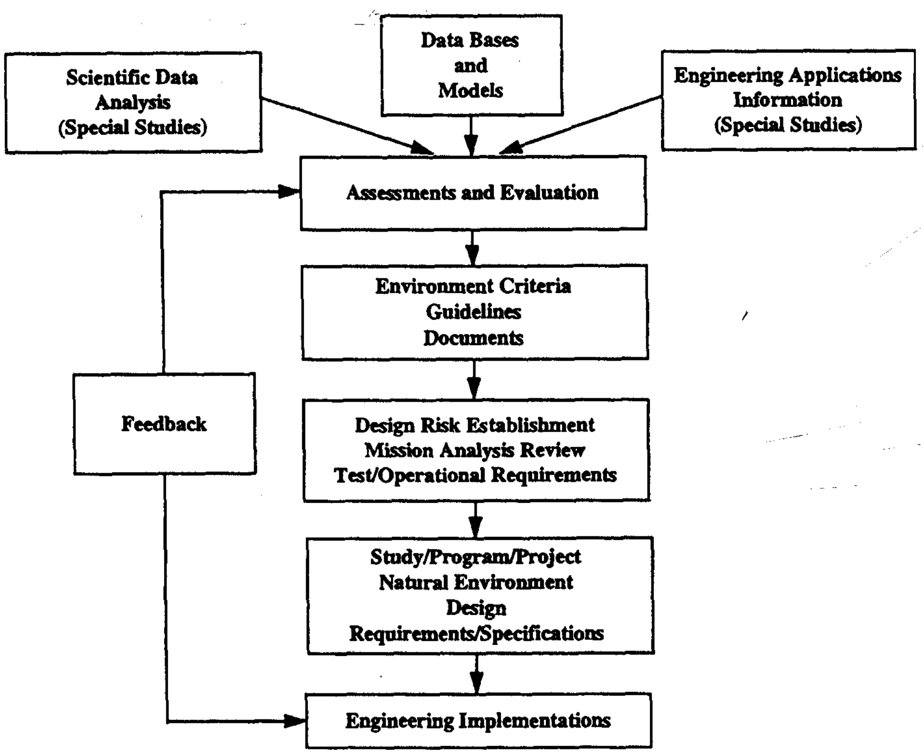

Figure 1. Natural Terrestrial Environment Definition and Analysis Process for Aerospace Vehicle Engineering Application

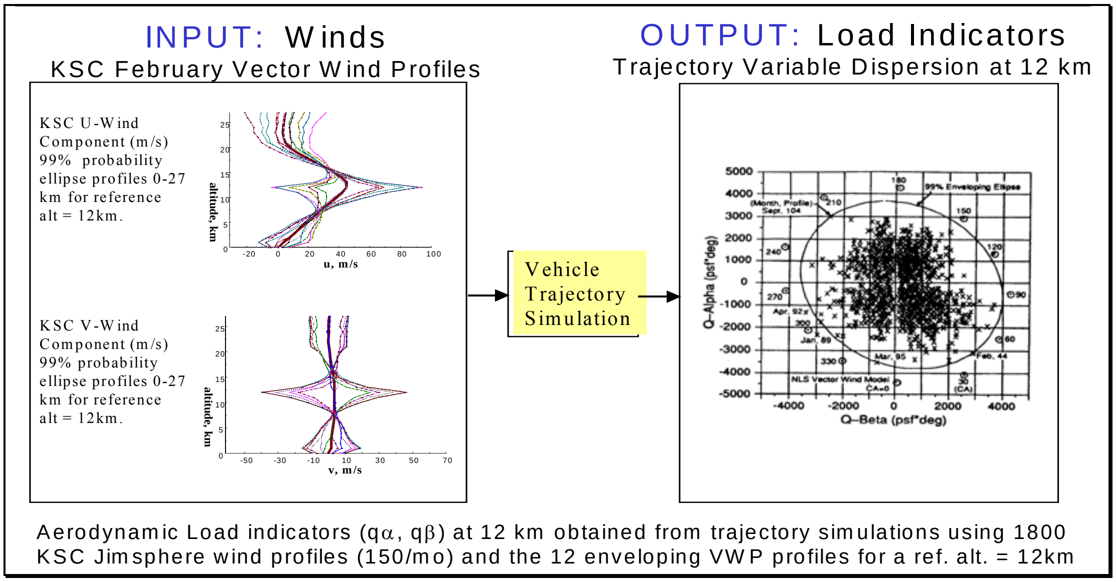

Figure 2. February KSC Vector Wind Profile Model Input in an Engineering Trajectory/Loads Example.

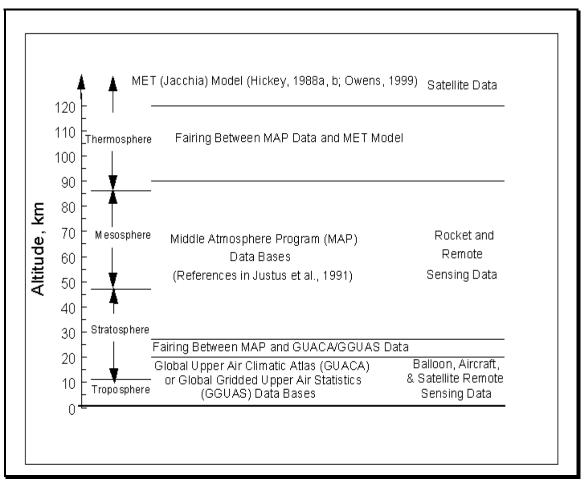

Figure 3. Schematic Summary of Atmospheric Regions and Data Sources Used in GRAM-99.

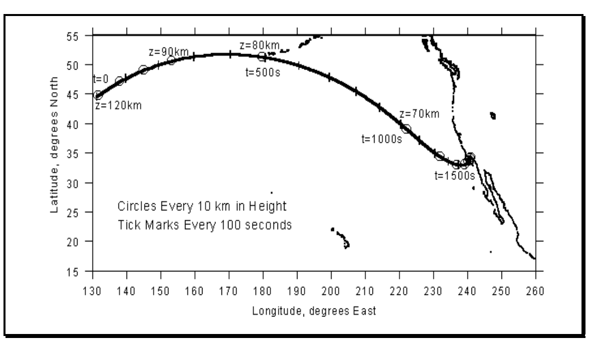

Figure 4. GRAM-99 Example of a Typical January Ground Track Re-entry Trajectory. 57° Inclination Orbit Landing at Edwards AFB.

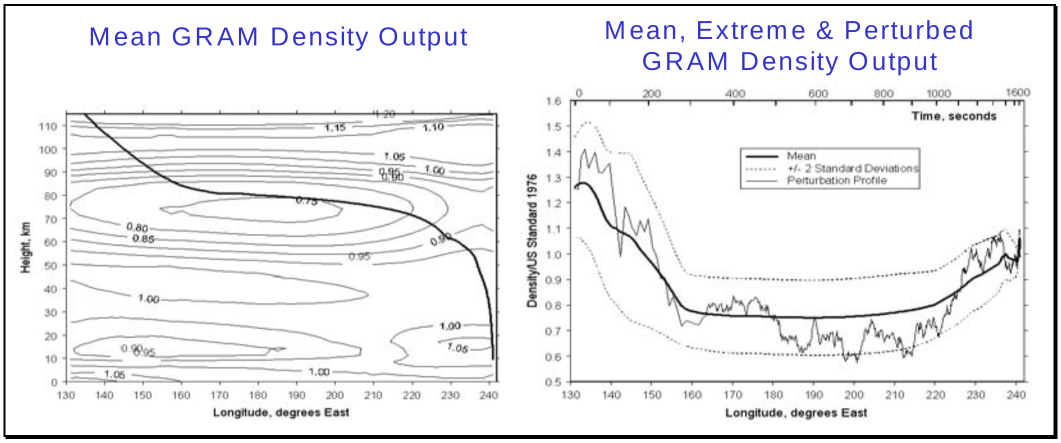

Figure 5. Resultant GRAM-99 Mean and Extreme Density Values Computed Along the Example January Re-entry Trajectory into Edwards AFB. Density is expressed as a ratio to the US76 Standard Atmospheric Density. Left figure is plot of mean January Density (vs. Height and Longitude). Right figure is Density Ratio vs. Longitude for Mean January, ±2-Sigma, and Monte-Carlo density realization.

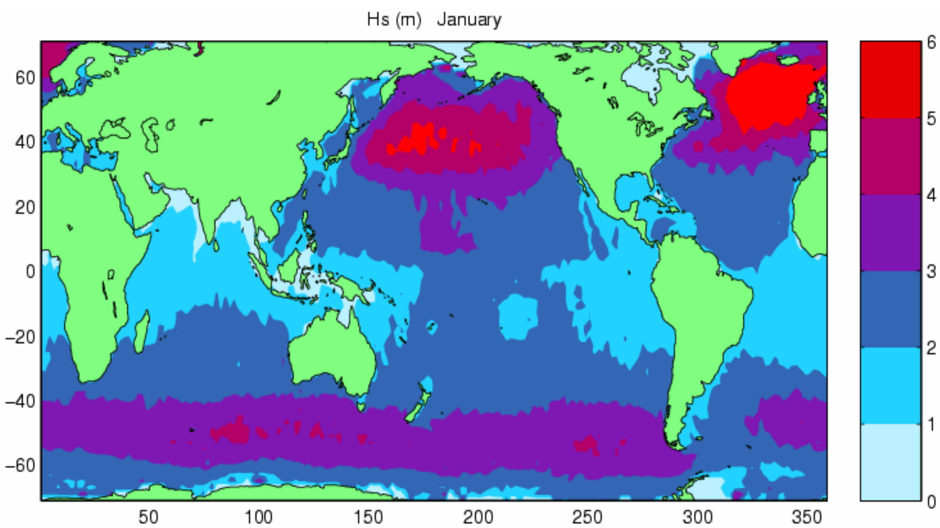

Figure 6. Global contour plot of mean significant wave height, Hs, in meters for the month of January. The darker (red) areas depict regions with wave height of greater than 5 m (16 ft.).

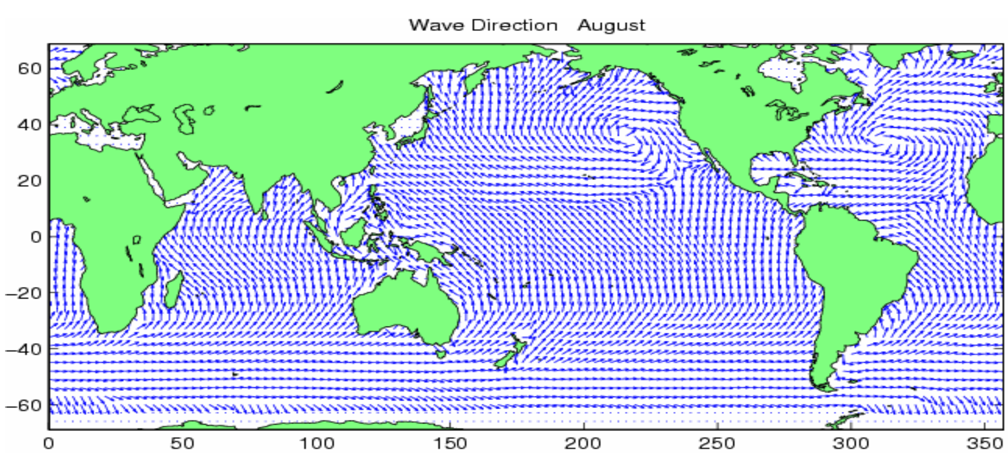

Figure 7. Global plot of mean wave direction for the month of August. Arrows indicate direction of wave travel. Note that longitudes are measured East rather than West.

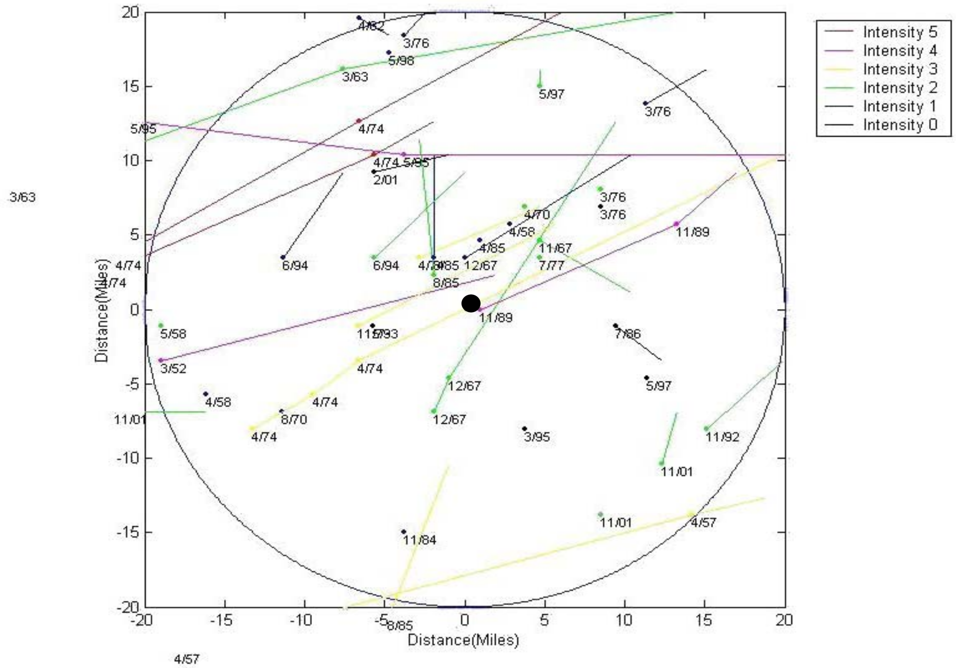

Figure 8. Tornado Tracks and Touchdowns within 20 miles of MSFC (1950-2001)

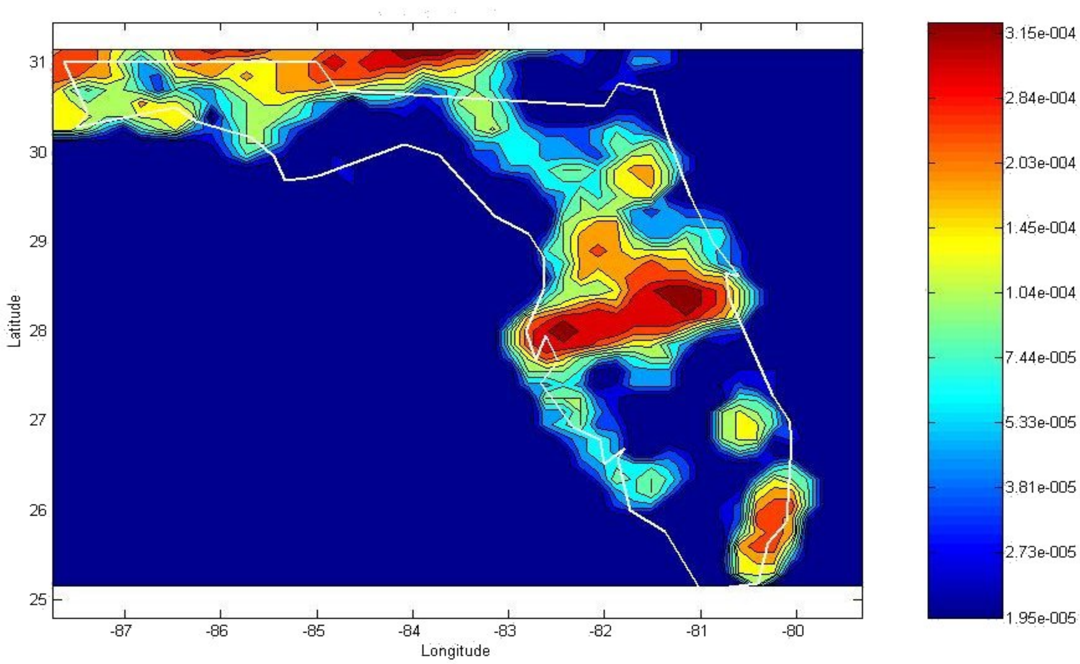

Figure 9. Tornado Probability Map for Florida (1950-2001)