Response Gap Estimates for Two Operating Areas in Prince William Sound

Report to Prince William Sound Regional Citizens' Advisory Council

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Executive Summary

Over the past 16 years, technological advancement in oil spill response systems, preparedness programs, and environmental monitoring have contributed to more proficient oil spill response operations in Prince William Sound (PWS). Yet, there are still times when oil is being shipped through PWS but environmental conditions, such as wind, waves, temperature, and visibility, preclude effective spill response operations. The PWS Response Gap is this window between the point of maximum mechanical response capacity and the established weather-based closure limits (15-foot seas or 45-knot winds at Hinchinbrook Entrance).

Prince William Sound Regional Citizens' Advisory Council (RCAC) has commissioned a study to identify and determine the frequency of the Response Gap in two areas of Prince William Sound. A Methods Report, describing the proposed methods, data, and analyses to be used in this study, was developed, reviewed, and approved in April 2006.

To quantify the Response Gap for PWS, this study began by assembling historical datasets of the environmental factors known to affect the open-water mechanical response system used in PWS. Datasets were developed for two of the operating areas in PWS: Central PWS and Hinchinbrook Entrance. Each dataset contained observations related to four environmental factors: wind, sea state, temperature, and visibility (limited to daylight and darkness). These datasets were used in a "hindcast" to evaluate how often environmental conditions exceed the maximum response operating limits while Hinchinbrook Entrance closure limits were not reached.

The most subjective part of this analysis was determining the response operating limits. Ultimately, the limits were established based on the best professional judgment of the authors of this report. We based the limits on a thorough review of the published literature, existing contingency plans, regulatory standards, and after-action reports, with the objective of establishing realistic limits for the existing open-water response system. Response limits were coded using the colors red (response not possible), yellow (response possible but impaired), and green (response possible) to identify whether the limits were met for a particular environmental factor during each operational period.

A Response Gap Index (RGI) was calculated to incorporate the interactions between environmental factors and response efficiency losses based on our established response limits. Once the RGI was computed for each observational period, the dataset was summarized to produce a realistic estimate of the amount of time that the Response Gap existed in the two PWS operating environments studied here. The RGI is expressed as a percentage of time that a response was not possible, but the Hinchinbrook Closure limits were not exceeded. Hinchinbrook Entrance was at or beyond weather closure conditions just 1.7% of the time during the study period.

In Central PWS, none of the factors exceeded the point at which mechanical response would be precluded even 2% of the time when considered independently. However, when environmental factors were considered together, the response limitations were exceeded 12.6% of the time, annually. Not surprisingly, the response limits were exceeded more often in winter (23.1% of the time) than in summer (4.2% of the time).[1]

At Hinchinbrook Entrance, sea state exceeded the operating limits 19.2% of the time and wind exceeded the limits only 2.9% of the time. When the environmental factors were considered together, the response limitations were exceeded 37.7% of the time. Again, the response limits were exceeded more often in winter (65.4% of the time) than in summer (15.6% of the time).

When both operating areas were considered together, the response limitations were exceeded 38.5% of the time. Response limitations were exceeded more often in winter (66.1%) than in summer (16.2%). These results are very similar to the Hinchinbrook Entrance results, as there were few times (~ 2%) when the Central PWS conditions reached levels where mechanical response would be precluded but when conditions in Hinchinbrook Entrance did not preclude a response

This study was made challenging by a paucity of reliable environmental data and the subjective nature of determining response limitations for the open-water response system. Also, applying the RGI calculations presented here to predict the frequency of the Response Gap in the future relies on two assumptions: a) that past weather is a reliable predictor of future weather, and b) that open-water response systems will remain the same in terms of their response limitations. With a changing climate and the associated potential for increased storm events, along with the potential for response system improvements, it is recognized that the future Response Gap Indices may be different than those calculated for 2000-2005.

In order to reduce the amount of time when the Response Gap is in effect, either shipping must be limited further by severe weather conditions or response capabilities must improve, or both. Both options have associated costs. The datasets analyzed here showed that the existing closure limits were reached less than 2% of the time; changing the closure limits to parallel the response limits used in this study would close shipping through PWS nearly 30% of the time.

Increasing response capability might be accomplished in a number of different ways. However, it is difficult to evaluate means of increasing response capability until a quantitative approach is used to evaluate response limitations. This can be accomplished through field tests and modeling.

This study concludes with the following recommendations: 1) quantify response limitations, 2) add visibility measurements to the analysis, 3) conduct additional analyses on data assembled in this study, 4) explore ways to lower the Response Gap by increasing response capability, 5) conduct a Response Gap analysis in other operating areas of PWS, and 6) quantify response limitations and conduct a Response Gap analysis for the nearshore response system.

1 For the purpose of this study winter is October through March and summer is April through September.

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Introduction

The Prince William Sound Regional Citizens' Advisory Council (RCAC) has been working with crude oil tanker operators and regulators to promote strong oil spill response and prevention programs since before the Oil Pollution Act of 1990 (OPA 90).[2] RCAC has been a strong proponent of realistic oil spill contingency planning, including advocating for continual improvement of the Prince William Sound Crude Oil Tanker Oil Discharge Prevention and Contingency Plan (PWS Tanker C-plan) that covers crude oil tankers calling at the Trans-Alaska Pipeline's Valdez Marine Terminal and operating in Prince William Sound (PWS).

Over the past 16 years, technological advancement in oil spill response systems, preparedness programs, and environmental monitoring has contributed to more proficient oil spill response operations in PWS. Yet, there are still times when oil is being shipped through PWS but environmental conditions, such as wind, waves, temperature, and visibility, preclude effective spill response operations. The Response Gap is this window between the point of maximum mechanical response capacity and the established weather-based closure limits.

Appendix A provides a reference of the terminology used in this report.

Purpose of this Report

RCAC contracted Nuka Research and Planning Group, LLC to develop and implement a methodology to analyze the Response Gap in PWS.

This report is not intended to imply anything about PWS Tanker C-plan compliance with any law or regulation. Its scope is limited to the open-water response system currently described in the PWS Tanker C-plan and the selected operating areas. Neither does this report consider the nearshore response capability described in the same plan.

2 The RCAC website provides additional information about the mission and activities of the organization at: http://www.pwsrcac.org/about/index.html.

Goal and Objectives

This study sought to analyze the frequency of the Response Gap in PWS. This Response Gap exists when the Realistic Maximum Response Operating Limits (RMROL) for existing spill response technologies occur at conditions below the Hinchinbrook Entrance closure limits.

The following facts complicated this study:

- There are multiple, diverse operating areas in PWS and the environmental conditions may be very different at any given time. Environmental conditions can even vary considerably within operating areas.
- RMROL is affected by a number of environmental factors that interact with each other.
- Environmental factor data is sparse and not readily available for all operating areas in PWS.

We used a "hindcast" to estimate the probable distribution of environmental factors and the Response Gap Index (RGI) over time, and assembled a large dataset of environmental factors for the years 2000-2005. Application of the calculated Response Gap frequency to the present and future thus relies on the assumptions that a) past weather patterns–and associated environmental factors–will reflect future ones; and b) the limitations of open-water oil spill recovery systems will remain constant over time.

To complete the study, we:

1. Established the typical operating areas for open-water mechanical recovery systems in PWS.
2. Established the environmental factors that might limit oil spill response.
3. Assessed the availability of data for each environmental factor.
4. Determined which operating environments and environmental factors would be used for the purposes of this analysis.
5. Assembled available environmental factor data into datasets representative of selected operating areas.
6. Characterized the datasets of environmental factors using histograms and joint-probability distributions and correlated conditions within PWS to conditions at Hinchinbrook Entrance up to the closure threshold.
7. Flagged data observations for the times when Hinchinbrook Entrance was closed and ignored these observations in subsequent analyses.
8. Reviewed C-plans, published research, and oil spill response drill/exercise/spill after-action reports to assess the operational limits of each environmental factor on open-water oil spill response systems.
9. Established operational limits for each environmental factor, based on the review in Step 8 and best professional judgment.

10. Applied the operational limits to the datasets and characterized the results as frequency of occurrence distributions over time.
11. Established a rule to create a Response Gap Index representing the interaction between all environmental factors for a single observational period, based on best professional judgment.
12. Applied the rule to the datasets and characterized the results as frequency of occurrence distributions over time.

Background on Response Gap Issues

Legal and Regulatory Framework

This section of the report considers the legal and regulatory framework for issues related to the Response Gap, as well as the contents of the PWS Tanker C-plan.

STATE LAWS AND REGULATIONS

The possibility of a Response Gap has been established in Alaska State Laws and Regulations and the PWS Tanker C-plan since the early 1990s. State law requires anyone operating a tank vessel to have an Oil Discharge Prevention and Contingency Plan approved by ADEC.[3] Plan approval requires a demonstration of sufficient resources to meet the Response Planning Standard (RPS) for the planholder's operations.

RESPONSE PLANNING STANDARDS

The State of Alaska RPS that applies to the PWS Tanker C-plan requires the planholders to have sufficient oil discharge containment, storage, transfer, and cleanup equipment, personnel, and resources to contain or control and clean up a 300,000 barrel discharge within 72 hours.[4] The law is silent on the environmental conditions under which this standard must be met, but gives ADEC the authority to establish such details in regulation.[5]

ADEC's Oil and Hazardous Substance Pollution Control Regulations contain oil discharge prevention and contingency plan approval criteria, requiring the contingency plan to demonstrate that:

- The response system can be deployed in time to meet the RPS given assumed conditions for response operations, which must be described.[6]
- The RPS can be met under the conditions that might reasonably be expected to occur at the discharge site.[7]

3 Alaska Statutes: AS 46.04.030(c)
4 Alaska Statutes: AS 46.04.030(k)(1)(3)(b). This applies to tank vessels having a cargo volume of 500,000 barrels or more. Not all tank vessels operating in PWS are this large, but most are, so the PWS Tanker C-plan must meet the most stringent RPS.
5 Alaska Statutes: AS 46.04.030(e)
6 ADEC Regulations: 18 AAC 75.445(c)
7 ADEC Regulations: 18 AAC 75.445(d)(5)

ADEC recognizes that the RPS cannot be met under all environmental conditions and further establishes the concept of operating limitations in their regulations.

REALISTIC MAXIMUM RESPONSE OPERATING LIMITATIONS

ADEC regulations require that the contingency plan provide a description of the Realistic Maximum Response Operating Limitations (RMROL) that might be encountered during response operations. The plan must include an analysis of the frequency and duration of limitations that would render mechanical and other response methods ineffective. The RMROL, expressed as a percentage of time, must be defined through an analysis of the following environmental factors:

- Weather, including wind, visibility, precipitation, and temperature,
- Sea states, tides, and currents,
- Ice and debris presence,
- Hours of daylight, and
- Other known environmental conditions that might influence the efficiency of the response equipment or the overall effectiveness of a response effort.[8]

FEDERAL LAWS AND REGULATIONS

The Oil Pollution Act of 1990 (OPA 90) specifies that an operator of a tank vessel must have a contingency plan called a Vessel Response Plan (VRP).[9] The planning standard for a VRP is "to remove to the maximum extent practicable a worst case discharge (including a discharge resulting from fire or explosion)." Worst-case discharge is further defined as "in the case of a vessel, a discharge in adverse weather conditions of its entire cargo."[10]

Federal law sets additional standards for tankers loading at the Valdez Marine Terminal. These vessels must have "oil spill removal organization at appropriate locations in Prince William Sound, consisting of trained personnel in sufficient numbers to immediately remove, to the maximum extent practicable, a worst case discharge or a discharge of 200,000 barrels of oil, whichever is greater."[11]

The US Coast Guard (USCG) has established regulations under these laws. These regulations recognize the relationship between adverse weather and response capability: "the weather conditions will be considered when identifying response systems and equipment in a response plan for the applicable operating environment. Factors to consider include, but are

8 ADEC Regulations: 18 AAC 75.425(e)(3)(D)
9 United States Code: 33 USC Chapter 26 Subchapter III Section 1321(j)(5). This should not be confused with the "VERP," which is the port operations plan.
10 United States Code: 33 USC Chapter 26 Subchapter III Section 1321(a)(24)
11 United States Code: 33 USC Chapter 40 Subchapter II Section 2735(a)(2)

not limited to, significant wave height, ice, temperature, weather-related visibility, and currents within the Captain of the Port (COTP) zone in which the systems or equipment are intended to function."[12]

These regulations set a general planning standard for tank vessels carrying oil as a primary cargo, and specific planning standards for tank vessels loading at the Valdez Marine Terminal. In general, the VRP must provide for response resources suitable to a specified operating environment. Operating environments are broken into four categories with the characteristics shown in Table 1. While most of the waters in the PWS region are considered inland waters, the COTP has classified PWS as an "ocean" operating environment.

Additional criteria to be evaluated include the following environmental factors:

- Ice conditions,
- Debris,
- Temperature ranges, and
- Weather-related visibility.[13]

However, the federal regulations clearly state that "(t)hese criteria reflect conditions used for planning purposes to select mechanical response equipment and are not conditions that would limit response actions or affect normal vessel operations." [14]

Table 1. Operating environment and characteristics set out in federal regulations.[15]

Operating Environments	Significant Wave Height	Sea State
Rivers and Canals	≤ 1 feet	1
Inland	≤ 3 feet	2
Great Lakes	≤ 4 feet	2-3
Ocean	≤ 6 feet	3-4

ASTM Operating Environment Classifications

The American Society for Testing and Materials (ASTM) has established another scheme for classifying operating environments in order to determine if oil spill response equipment is appropriate (ASTM, 2000). ASTM (2000) states that "(t)hese classifications may be used in formulating standards for design, performance, evaluation, contingency and response planning, contingency and response plan evaluation, and standard practice for spill control systems."

12 Federal Regulations: 33 CFR Part 155 Subpart D Section 155.1020.
13 Federal Regulations: 33 CFR Part 155 Subpart D Section 155.1050(a)(2).
14 Federal Regulations: 33 CFR Part 155 Subpart D Section 155.1050(a)(1)(ii).
15 Federal Regulations: 33 CFR Part 155 Appendix B Table 1.

Table 2 shows the ASTM classifications. This classification system is also used in the World Catalog of Oil Spill Response Products (Potter, 2004) and the Spill Tactics for Alaska Responders manual (ADEC, 2006).

We have chosen to use the same classification scheme for this study. The open-water class in the ASTM scheme corresponds to the ocean class in the USCG scheme, which is the operating environment specified for PWS.

Table 2. ASTM F625 water body classifications.

Type[a]	Wave Height[b] meters (feet)	Examples of General Conditions
Calm-water	0 to 0.3 (0 to 1)	Small, short, non-breaking waves
Protected-water	0 to 1 (0 to 3)	Small waves, some whitecaps
Open-water	0 to 2 (0 to 6)	Moderate waves, frequent whitecaps
Open-water (rough)	>2 (>6)	Large waves, foam crests and some spray

a. If current is significant, approximately 0.4 m/s (0.8 knots) or more, append "C" to the descriptor type, as "I-C."
b. Significant wave height throughout. May include breaking waves. The ratio of wave height to wave length should also be considered. The orientation of waves to current direction should also be considered.

PWS Tanker C-plan

OPEN-WATER MECHANICAL RECOVERY SYSTEM

The Ship Escort and Response Vessel System's (SERVS) current open-water oil spill recovery system for Prince William Sound is comprised of four barge-based recovery and storage systems and one dynamic, inclined-plane skimming vessel.[16] The recovered fluid storage capacity of the barges ranges from 137,000 to 191,000 barrels. Each barge has three high volume, weir-skimming systems for recovering oil concentrated with a gated U-boom array and contained in a standard U-boom. Each barge is part of a Task Force that includes a tug to control the barge and four workboats or fishing vessels to handle the boom.[17] The Task Force requires each of its parts to function in order for the system to accomplish the recovery tactic. *If any component of the system (people, vessels, booms, barges, or skimmers) fails, then the system cannot successfully collect oil.* Therefore, the effect of every environmental factor on every component of the system must be considered when determining operational limits.

This study focused on the four barge-based, open-water mechanical recovery systems, or Task Forces, because they account for 87% of the response capability (ANVIL Engineering, 1994) necessary to meet the 300,000 bbl RPS.

This Response Gap analysis was based on the PWS Open-water Oil Spill

16 PWS Tanker C-Plan, 2002, Part 3, SID 1, Section 1.
17 PWS Tanker C-Plan, 2002, Part 3, SID 1, Section 2.

Recovery System as described in the C-plan. Specifically, Tactic O-1 TransRec/GrahamRec Task Force is the primary tactic to be used for open water recovery. The other recovery tactics would be as susceptible or more susceptible to environmental limitations.

The C-plan lists the following components necessary to deploy Tactic O-1:

1 ea. Skimmer/storage barge

1 ea. Tug

3 ea. Large volume skimmers

4 ea. Workboats or fishing vessels of sufficient size and horsepower

2 ea. Boom sections

Each of these components, including the personnel that operate them, is necessary for the successful implementation of the tactic and each is affected differently by environmental factors. Theoretically, the response limit of the system is realized once any one component reaches a limit. Therefore, in considering the limits to the system as a whole, we focused on those components that we have observed or experienced to be most susceptible to environmental conditions. In our opinion, the components most susceptible to limitation or failure due to wind and sea state are the booms, skimmers, and boom deployment vessels. For the purpose of this analysis, we assumed that the following types of boom, skimmer, and deployment vessels would be used:

Item	Type	Make/Model	Amount
Boom - Gated	Open Water	Kepner Sea Curtain	3,000 feet
Boom - U	Open Water	Vikcoma Ocean Boom	1,320 feet
Skimmer	Open Water	TransRec 350	3 ea.
Boom Towing Vessels	Large Seiner	41 to 58 feet	4 ea.

Although Tactic O-1 does not specify this exact equipment, it is representative of the equipment available in Prince William Sound stockpiles and likely to be used for on-water recovery (based on past drills and exercises). Other variations on this equipment set are possible and could alter the Response Gap. For example, if smaller boom towing vessels are used, the Response Gap will be larger. Likewise, different boom or skimmers could also change the Response Gap.

REALISTIC MAXIMUM RESPONSE OPERATING LIMITATIONS

As required by state regulation, the PWS Tanker C-plan has had a RMROL section in each of the last three plan submittals (1995, 1998, 2002).[18] The plan writers acknowledge the regulations discussed above and

18 The 1998 and 2002 sections are identical.

recognize the difficulty of determining the RMROL. They recognize that the interactions between environmental factors make it very difficult to set a hard and fast response limit. The operational limits for the mechanical response system in Table 3 are reported in the RMROL section of the C-plan with many caveats.

Table 3. RMROL reported in the 1998 and 2002 PWS Tanker C-plan for mechanical response operations.

Environmental Factor	Conditions that Could Preclude a Response
Wind	*Winds > 30 to 40 knots, but depending on other variables.* The negative impact of winds on the effectiveness of a response is realized when winds approach a range of 30 to 40 knots or greater. Temperature, sea state, visibility, and precipitation may vary the effect of a specific wind speed. In some circumstances, a response may be possible in 30- to 40-knot winds, while in other circumstances a response may not be effective in winds less than 20 knots.
Sea State	*Seas greater than 3 m (10 feet) with strong tides and currents.* A rule-of-thumb RMROL for wave height is 3 m* (10 feet). This limitation may be affected by ambient temperature, visibility, and precipitation. The impact of tides and currents can only be determined on a case-by-case basis.
Visibility	*Depending on other environmental factors, the visibility limitation may be <0.5 nautical miles for vessels tracking oil.* If wind, sea state, temperature, visibility and/or precipitation cause the response to be inefficient, the additional factor of darkness may actually impede a response. Limitations for flight surveillance operations, based on visual flight rules for rotary- and fixed-wing aircraft are: 500 foot ceiling and 1-mile visibility if in sight of land, or 500 foot ceiling and 3-mile visibility if over open-water and land is not in sight. For booming and skimming vessels, the visibility limitation varies between 0.125 nautical miles (200 meters) and 0.5 nautical miles (800 meters), depending on temperature, sea state, wind, and precipitation. A RMROL for visibility affects response vessels differently depending or whether they are already engaged in oil recovery or seeking oil to recover. For vessels actively booming and skimming in oil, the master of the vessel would set limits based on safety and operational efficiency. For vessels not in oil and which may require aircraft surveillance, the limitations would likely determined by those of the aircraft as described above. A RMROL based solely on hours of daylight can only be determined on a case-by-case basis.
Temperature	*Long-term temperatures below freezing combined with high winds could preclude a response.* Sustained temperatures below freezing, in conjunction with high winds, severe sea states, poor visibility, and/or heavy precipitation, will significantly reduce the effectiveness of the response. At temperatures below 15ºF and winds of 24 to 28 knots, wind chill becomes a factor in response operations.

* A Norwegian study of TransRec 350 weir-skimming system performance supported this rule-of-thumb, concluding that the maximum wave height for effective operation of this system is 3 m (Nordvik, 1999).

Environmental Factors' Limitations on Mechanical Response

A number of environmental factors affect the efficiency of a mechanical oil spill response system. There are interactions among these factors, and response efficiency does not decline in a linear fashion as environmental conditions deteriorate.

WIND

Wind is a common phenomenon that affects any marine environment. Wind is the primary driver of ocean waves, but sea state will be considered as a separate factor. Wind alone can impede or prevent mechanical response operations in the following ways:

- Vessels unable to keep on station,
- Crew unable to work on deck,
- Equipment and workboat deployment and retrieval impeded, and
- Boom failure.

SEA STATE

Sea state refers to both wave height and wave period (frequency). When wave height is small, wave period has little effect on response operations. As wave height increases, waves of a short period have greater effect on response operations than waves of a longer period. Short, choppy waves have a greater effect than long, ocean swells. Waves can impede or prevent mechanical response operations in the following ways:

- Boom failure,
- Vessels unable to keep on station,
- Skimmer failure,
- Crew unable to work on deck,
- Equipment and workboat deployment and retrieval impeded,
- Oil becoming submerged and thus not available to recovery, and
- Inability to track and encounter oil.

VISIBILITY

Visibility can be hampered by darkness, fog, snow, heavy precipitation, or low clouds. Visibility can impede or prevent spill response operations in the following ways:

- Inability to track and encounter oil, and
- Vessels unable to keep on station.

TEMPERATURE

High and low temperature extremes can adversely affect oil spill response operations, but in PWS low temperatures are more likely to cause problems. Low temperature can impede or prevent response operations in the following ways:

- Crew unable to work on deck due to ice or hypothermia,
- Mechanical equipment failure due to icing, and
- Vessel instability due to icing.

CURRENTS

Currents can significantly impact oil spill response operations, but because ocean currents occur over a broad area, they have less effect than the currents found in rivers or narrow embayments. The entire response system is captured in the current and there is little or no relative movement between the various components of the response system. However, currents can cause problems in areas where eddies or tide rips occur and when the current sets the response system into shoal waters. Currents can impede or prevent response operations in the following ways:

- Boom failure,
- Oil becoming submerged and thus not available to recovery, and
- Vessels unable to keep on station.

Because only ocean currents are likely to be encountered by the open-water response systems operating in PWS, and there is no way to measure local currents such as tide rips, currents were not considered for the purposes of this study.

ICE

Ice can impede or prevent response operations in the following ways:

- Failure of skimming systems,
- Vessels unable to keep on station,
- Boom failure, and
- Inability to track and encounter oil.

Ice is not a common phenomenon in PWS: significant amounts occur only near Columbia Bay. Ice is not considered for this phase of this study, because ice is not a common phenomenon in the selected operating areas of Central PWS or Hinchinbrook Entrance.

OTHER ENVIRONMENTAL FACTORS

Other environmental factors such as precipitation, debris, and tides can conceivably impact oil spill response operations, but are not considered significant to this study.

Interactions Between Environmental Factors

Interactions between environmental factors have a big effect on response operating limits. For example, low temperatures and strong winds cause freezing spray that can impede or prevent response operations much sooner than either temperature or wind alone. Likewise, waves of a certain height are much more limiting in the presence of a strong wind or in times of low visibility. We accounted for these interactions by developing a simple set of rules to develop a Response Gap Index (RGI) for each observational period.

Response Capability Degradation

The degradation of response does not occur at a single point, nor is it necessarily linear in nature. For instance, response efficiency does not go from 100% to 0% as wind increases from 29 to 30 knots. Likewise, a wind of 15 knots does not indicate that the response efficiency is half that at 30 knots. The degradation curve is probably different for each environmental factor. This further complicated the task of setting discrete operational limits. We accounted for capability degradation by establishing categories of limitations for each environmental factor. These categories are further explained below.

Methods

The following methods were used to develop the hindcast of the Response Gap probabilities in Prince William Sound.

Selected Operating Areas

Prince William Sound is a large inland sea formed between the glaciated Chugach Mountains and the northern coastline of the Gulf of Alaska. Many factors influence the weather and sea conditions in PWS. Weather and sea conditions are markedly different between winter and summer. At any one time, conditions can be very different in different parts of PWS. On any single day, conditions may change dramatically. We divided PWS into operating areas where environmental conditions might be similar across the entire area. We balanced the recognition that micro-climates still exist in any operating environment against the need to define an area that has similar environmental conditions and observations available.

The 1995 PWS Tanker C-plan describes the following four response zones in the Prince William Sound Subarea:

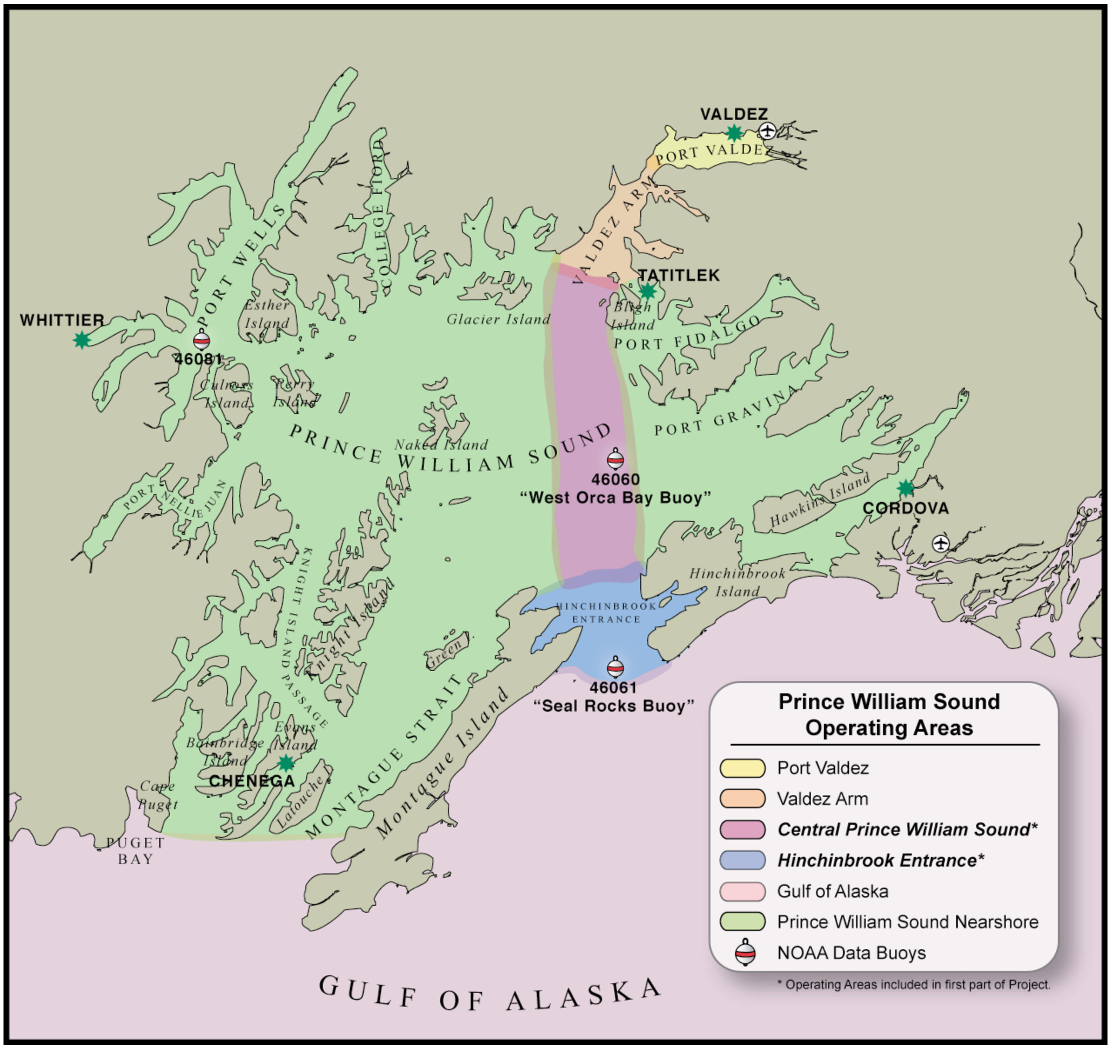
- Port Valdez,
- Valdez Arm,
- Central PWS, and
- Hinchinbrook Entrance.

We agreed that these zones describe distinct operating areas and we added two more:

- Gulf of Alaska outside PWS, and
- Nearshore areas in PWS that are away from the tanker lanes.

Figure 1 depicts the operating areas to be used in this study.

Figure 1. Prince William Sound operating areas.



Of the six operating areas defined for Prince William Sound, only two had sufficient data readily available for analysis: Central PWS and Hinchinbrook Entrance. Data from the National Oceanic and Atmospheric Association's (NOAA) National Data Buoy Center's (NDBC) Buoys 46060 (West Orca Bay) and 46061 (Seal Rocks)[19] gave readily-available, accurate observations for wind speed, wave height, wave period, and temperature. We chose to limit the analysis to these two operating areas.

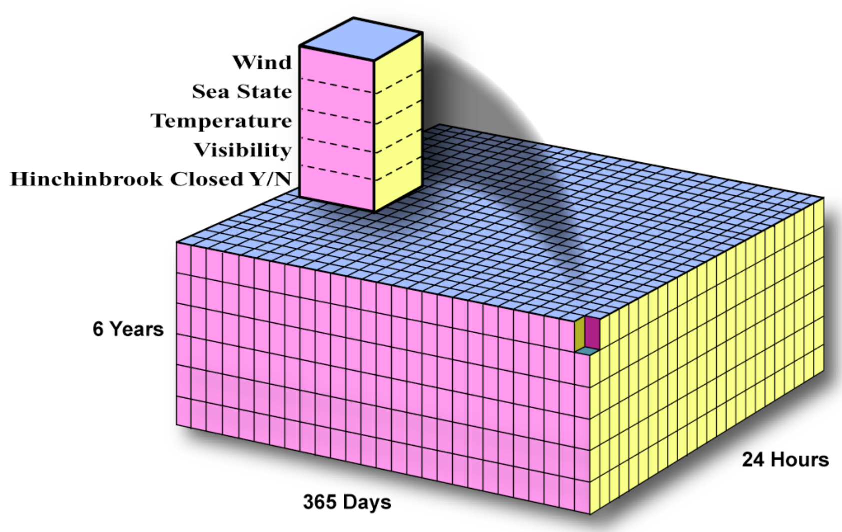
The Glosten Associates was contracted to complete the following statistical analyses[20]:

1. Reviewed and assimilated PWS meteorological and oceanographic data, specifically wind speed, wave height and period, air temperature, and visibility (the independent variables for the RGI), and identified the statistical distribution of the range of conditions that may be encountered in this environment.
2. Obtained a statistical distribution of the wind and waves within Central PWS, correlated to the conditions at Hinchinbrook Entrance up to the closure conditions (15 foot seas or 45 knot winds).

Assembling a Dataset of Environmental Factors for Each Operating Area

A dataset of environmental factors was assembled for both selected operating areas. Figure 2 depicts the nominal size of the matrix for each dataset, consisting of hourly observations over 6 years. Each cell of the matrix contains observations for four environmental factors (whenever observations were available): wind, sea state, air temperature, and visibility.

Figure 2. The dataset matrix.



19 Note that NOAA Buoy 46060 (West Orca Bay) is commonly referred to as the "Mid-Sound Buoy."
20 The Glosten Associates' contribution was limited to the statistical analyses described here. Nuka Research and Planning Group developed the response limits used.

Table 4 summarizes the data sources used for each component of the datasets. Buoys 46060 and 46061 provided most of the raw data for analysis.

Table 4: Data used for each environmental factor.

Environmental Factor (units)	Data Source	Comments
Wind (knots)	Buoys 46060 and 46061	None.
Sea state (wave height in feet and wave period in seconds)	Buoys 46060 and 46061	Because the short-period waves are more detrimental to response operations than long-period waves, a wave steepness parameter was calculated to distinguish between swell and wind driven waves. The wave steepness parameter (WSTP) is calculated as **WSTP = WVHT / (*g* X DPD²)**, where: WVHT=Significant wave height, calculated as the average of the highest one-third of all of the wave heights during the sampling period, g=the acceleration due to gravity (32.174 ft/s²), and DPD=Dominant wave period is the wave period with maximum wave energy.
Temperature (°F)	Buoys 46060 and 46061	None.
Visibility	Civil twilight tables	Reliable observations of visibility during daylight hours were difficult to obtain, so the only visibility restriction considered for this phase of the study was due to darkness. Using only daylight/darkness visibility restrictions resulted in a conservative estimate of the Response Gap.
Hinchinbrook Status	Each hourly set of observations in the matrix included another bit of data. A flag was set to indicate if Hinchinbrook Entrance was opened or closed at the time of the observation. This information was calculated from data obtained at the Seal Rocks Buoy; if WSPD equaled or exceeded 45 knots or if WVHT equaled or exceeded 15 feet, then Hinchinbrook Entrance was deemed closed. Observations for times when Hinchinbrook Entrance was closed were not considered when determining the response limits.	

MISSING DATA OBSERVATIONS

The objective was to assemble 6 years' worth of recent data, for a total of 6 years x 365 days x 24 hourly observations, to enable a meaningful statistical analysis. Data were assembled for both operating areas for the years 2000 through 2005.

The number of hourly observations available ranged from about 4,300 to about 8,700 per year for Buoy 46060, for a total of about 46,000 valid observations over the 6-year period. For Buoy 46061, the number of hourly observations available ranged from about 6,700 to 17,500 (in 2005, an observation was made at every hour and 30 minutes past the hour), for a total of about 57,000 valid observations over the 6-year period. The monthly and annual completeness of the datasets are shown in the Figures 3–6.

Figure 3. Completeness of wind speed and wave height data by month in the Central Sound (NOAA Buoy 46060).

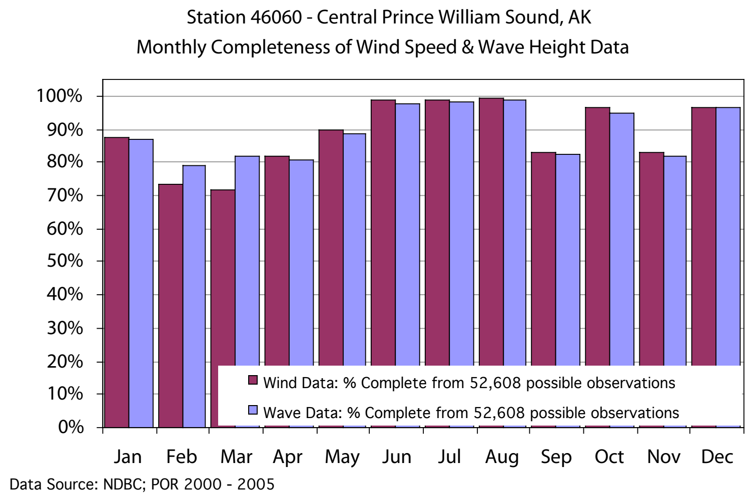


Figure 4. Completeness of wind speed and wave height data by year in the Central Sound (NOAA Buoy 46060).

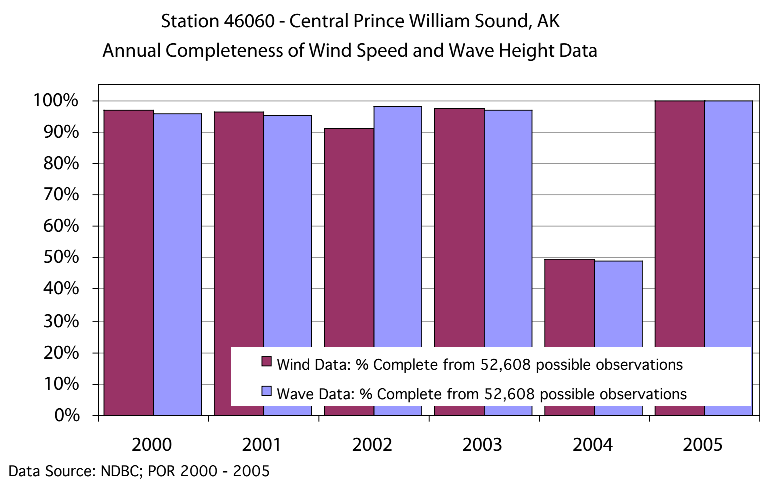


Figure 5. Completeness of wind speed and wave height by month at Hinchinbrook Entrance (NOAA Buoy 46061).

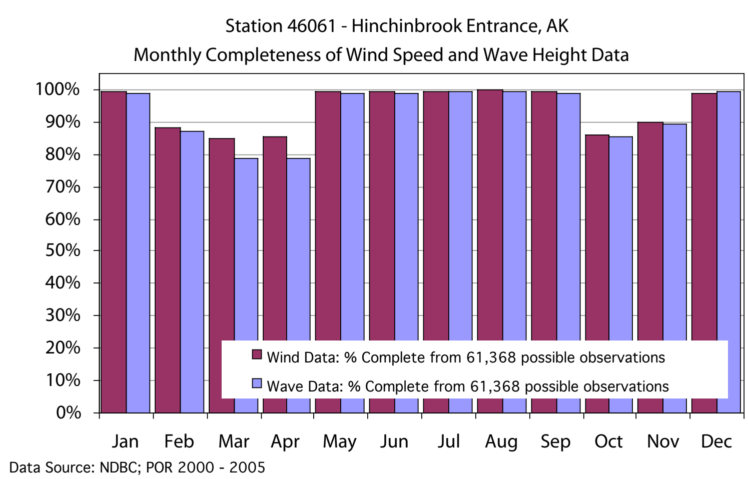
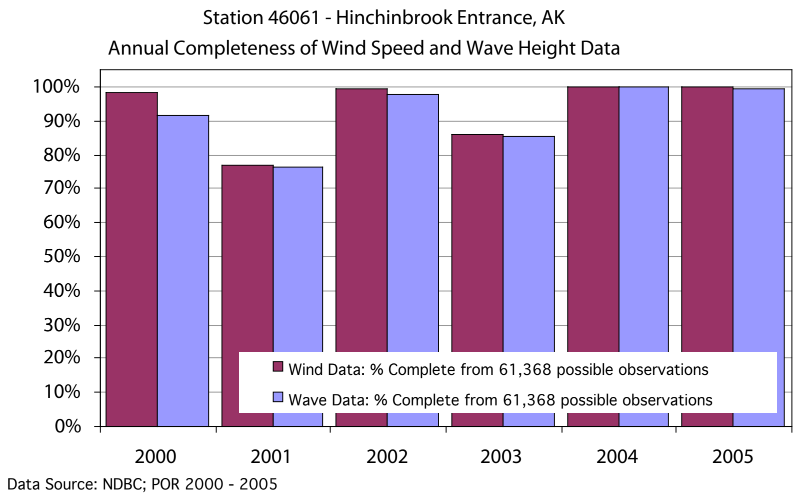


Figure 6. Completeness of wind speed and wave height data by year at Hinchinbrook Entrance (NOAA Buoy 46061).



Characterization of Environmental Factor Datasets

A single dataset was assembled by aligning the hourly observations from the Central PWS data buoy with concurrent observations from the Hinchinbrook Entrance data buoy. Upon omitting data gaps (notably in 2004), a data set was generated containing about 42,000 concurrent observations for Central PWS and Hinchinbrook Entrance from 2000 through 2005. To this dataset, civil-twilight data from Valdez were added.

Once assembled, the dataset was analyzed statistically to provide insights into the various environmental conditions found in the two operating areas. The following results were generated:

- Histograms and cumulative-distribution plots of significant wave height, (WVHT), wind speed (WSPD), wind direction, wind gusts, and air temperature from buoys 46060 and 46061,
- Joint-probability-distribution plots of wave height (WVHT) and modal wave period (DPD): annual, winter, and summer, and
- Daylight curves, based on the civil-twilight data.

Literature Review

It was useful to review published and un-published reports concerning the operating limits of various response systems. Prior to establishing limits for this study, we reviewed relevant published literature and reports and assembled an annotated bibliography.

We were most interested in un-published reports, especially after-action reports from oil spill drills, exercises, trainings, and actual responses. Actual observations of the conditions where response systems become limited are much more valuable than tests on a single component of the system. We made inquiries with the following organizations and requested information from after-action reports that would be useful in establishing response operating limits:

- Alaska Chadux,
- Alaska Clean Seas (ACS),
- Alaska Department of Environmental Conservation (ADEC),
- Alyeska Pipeline Service Company,
  Ship Escort and Response Vessel Service (SERVS),
- Australian Marine Oil Spill Centre,
- Briggs Marine Environmental Services, Ltd.,
- Burrard Clean Operations,
- California Department of Fish and Game,
- Canadian Coast Guard,
- Cook Inlet Spill Prevention and Response Inc. (CISPRI),
- East Asian Response Limited,
- Environmental Protection Agency (EPA),
- Global Salvage & Diving,
- Marine Spill Response Corp. (MSRC),
- National Ocean and Atmospheric Administration (NOAA), HazMat
- National Response Corp (NRC),
- Ocean Advocates,
- OHMSETT,
- Oil Spill Response Limited (OSRL),
- Oregon Department of Environmental Quality,
- PWS Regional Citizens' Advisory Council (RCAC),
- PWS Response Plan Group (RPG),
- Southeast Alaska Petroleum Response Organization (SeaPro),
- Shoreline Environmental Research Facility,
- SL Ross,
- US Coast Guard (USCG), and
- Washington Department of Ecology.

Some of the organizations would not provide their reports or data on response limitations. Many more did not have their after-action reports organized in a fashion that allowed them to provide any information on response limitations.

Published articles collected for the literature review tended to focus on the development of statistical models and laboratory experiments, and did not draw operational conclusions.

Response Operating Limits

The most subjective part of this analysis was determining the response operating limits. Ultimately, the limits were established based on the best professional judgment of the authors of this report.[21] We attempted to base the limits on a thorough review of the published literature, existing contingency plans, regulatory standards, and after-action reports, with the objective of establishing realistic limits for the existing open-water response system.

Table 5 contains the limits that were used in this Response Gap analysis for the open-water recovery system. A discussion follows of how each of these limits was established.

Table 5: Limits used for the Prince William Sound open-water recovery system Response Gap analysis.

Environmental Factor	Green Response Not Impaired	Yellow Response Impaired	Red Response Not Possible/Effective
Wind (knots)	0 to < 21	21 to < 30	≥ 30
Sea State (feet)	≤ 3 when wave steepness parameter is greater than or equal to 0.0025, otherwise ≤ 4	> 3 to < 6 when wave steepness parameter is greater than or equal to 0.0025, otherwise > 4 to < 8	≥ 6 when wave steepness parameter is greater than or equal to 0.0025, otherwise ≥ 8
Temperature (ºF)	≥ 26 at any wind speed, or otherwise as not included in yellow or red conditions	>16 to < 26 and wind speed ≥ 12 knots	≤ 16 and wind speed ≥ 5 knots
Visibility (nautical miles)	≥ .5 (day light)	.5 to .25 (civil twilight darkness)	< .25 (not used for 2006 analysis)

WIND

Wind can affect the ability of boom to contain oil[22] and the ability of a vessel to maintain station while towing boom or a recovery/storage barge. Since open water sea states are often driven or influenced by the wind,

21 The Glosten Associates were not part of determining operational limits; the limits were established by Nuka Research and Planning Group.

22 Kim et al. (1998) described the three methods of boom failure as occurring when 1) oil splashes over the boom, 2) oil escapes under the boom, and 3) oil separates from the oil-water interface, which is called entrainment. Fang and Johnston (2001b) conclude from statistical modeling and laboratory experiments that the waves and wind compromise oil containment when a current is present.

there is very little empirical data to show when wind alone (absent sea state) will become limiting to boom or towing. The Realistic Maximum Response Operating Limits (RMROL) section of the C-plan[23] states that winds of 30 to 40 knots could preclude a response, depending on the impact of other variables.

Table 6 shows the Beaufort scale and the expected sea states for a range of winds blowing across an open ocean with deep water, no current, and great fetch.

Table 6: Beaufort scale of ocean conditions, wind speed, and probable sea state (Environment Canada, 1996).

Beaufort Scale	Wind Speed (Knots)	Probable Sea State (Feet)	Effects at Sea*
0	< 1	Calm	Sea is mirror-like.
1	1 to 3	< .25	Scale-like ripples form. No crests.
2	4 to 6	.5 to 1	Small wavelets: short but more pronounced. Crests are glassy and do not break.
3	7 to 10	2 to 3	Large wavelets: crests begin to break. Foam is glassy. Scattered white horses possible.
4	11 to 16	3.5 to 5	Waves small but lengthening. More frequent white horses.
5	17 to 21	6 to 8.5	Moderate waves take longer form. Many white horses.
6	22 to 27	9.5 to 13	Large waves. White foam crests are more extensive and there is probably spray.
7	28 to 33	13.5 to 19	Sea heaps up. White foam from breaking waves begins to be blown in streaks.
8	34 to 40	18 to 25	Moderately high waves. Breaking crests form spindrift. Streaks of foam appear.
9	41 to 47	23 to 32	High waves. Dense streaks of foam along the direction of the wind. Crests unstable. Spray may affect visibility.
10	48 to 55	29 to 41	Very high waves with long over-hanging crests. Foam blown in dense, white streaks along the direction of the wind. Sea looks white. Sea tumbling becomes heavy and shock-like. Visibility affected.
11	55 to 63	37 to 52	Exceptionally high waves. Sea completely covered with long, white patches of foam lying along the direction of the wind. Edges of wave crests blown into froth. Visibility affected.

* Pictures can be found on the Environment Canada website at: http://www.msc-smc.ec.gc.ca/msb/manuals/manmar/app6_e.html.

23 PWS Tanker C-Plan, SID 1, Section 12 Realistic Maximum Response Operating Limitations.

The National Weather Service has established "small craft" generally as vessels less than 65 feet (National Weather Service, 2005). In Alaska, the lower limit of a "Small Craft Advisory" is reached when predicted or actual sustained wind speeds of 23 knots extend for two hours or more (National Weather Service, 2006).

In the open-water environment, wind will cause waves to build; these wind-driven waves will be steep. As discussed below, steep waves have the most effect on vessels, boom, and skimmers.

Wind gusts may have less effect on sea state than sustained winds, but wind gusts can significantly affect response vessels and personnel. However, for the purpose of this analysis, the effects of gusts are not considered. The wind direction relative to currents, landmasses, and orientation of recovery operations can also affect the limits of response capability, but was not considered in this analysis.

Our experience is that winds greater than 20 knots begin to degrade the effectiveness of the open-water recovery systems and that at about 30 knots the systems become ineffective. Based on this experience, we used the following response limits for wind speed:

- Green: Effect is minimal or absent. Wind speed less than 21 knots.
- Yellow: Response operations possible but impaired. Wind speeds greater than or equal to 21 knots and less than 30 knots.
- Red: Response operations not possible or effective. Wind speeds greater than or equal to 30 knots.

SEA STATE

Sea state can affect the ability of boom to contain oil, the ability of skimmers to recover oil, and the ability of vessels to keep boom and recovery/storage barges on station. The RMROL section of the C-plan states that seas greater that 10 feet with strong tides and currents are conditions that could preclude a response.

Sea state may be measured in a number of different ways, including wave height, wave period, and wave steepness. Most oil spill literature uses only wave height as a measure of effectiveness. However, wave height can be misleading if wave period and steepness parameter are ignored. Response operations may be possible and effective in a 6-foot ocean swell and conversely may be ineffective in 4-foot, wind-driven waves. Wave steepness parameter has been used to distinguish between swell (long period waves with a steepness parameter of less than 0.0025) and wind waves (short period waves with a steepness parameter of greater than or equal to 0.0025). Confused seas can occur when waves appear from two or more directions. Confused seas can affect response capability, but are not considered for the purpose of this analysis.

The National Weather Service in Alaska issues a "Small Craft Advisory for Rough Seas" when actual or predicted sea states exceed 8 feet (National Weather Service, 2006).

Sea state is the primary measure used by the American Society for Testing and Materials (ASTM) and the USCG for classification of oil spill response equipment operating environments. Both the ASTM "open-water" operating environment and the USCG "ocean" operating environment are characterized by waves up to 6 feet. The boom and skimmers used in the PWS open-water recover system are only rated to sea states up to 6 feet.

Our experience observing drills and exercises is that in wind driven waves, open-water response systems can operate with little loss of efficiency in waves up to 3 feet. Above the 3-foot wave height, efficiency degrades and the response system becomes ineffective at wave heights around 6 feet. Based on this experience and the rating of the equipment, the Response Gap analysis used the following limits for wind-driven waves:

- Green: Effect is minimal or absent. Waves less than or equal to 3 feet when the steepness parameter is greater than or equal to 0.0025, or waves less than or equal to 4 feet when the steepness parameter is less than 0.0025.[24]
- Yellow: Response operations possible but impaired. Waves greater than 3 feet and less than 6 feet when the steepness parameter is greater than or equal to 0.0025, or waves greater than 4 feet and less than 8 feet when the steepness parameter is less than 0.0025.
- Red: Response operations not possible or effective. Waves greater than or equal to 6 feet when the steepness parameter is greater than or equal to 0.0025, or waves greater than or equal to 8 feet when the steepness parameter is less than 0.0025.

AIR TEMPERATURE

Cold air can affect the open-water recovery system in two significant ways: 1) it can create hypothermic conditions for responders, due to wind chill, and 2) it can cause icing conditions that can alter vessel stability. Both of these are safety considerations. Cold air can also affect response equipment, but this will occur at much lower temperatures and is not a consideration in this analysis. The RMROL section of the C-plan states that the combination of long-term temperatures below freezing with winds and waves could preclude a response.

Wind exacerbates both hypothermia and icing. Figure 7 shows the impact of wind and temperature on wind chill conditions. Figure 8 shows the impact of wind and temperature on marine icing conditions. Hypothermia can be prevented by proper protection of response personnel and by regularly rotating personnel inside for warm-up. However, the C-plan does

24 Based on extensive prior analysis of wave data measurements from data buoys, The Glosten Associates determined that a wave steepness parameter value of 0.0025 represents an appropriate threshold between swell and wind-driven seas in PWS. This threshold is indicated in, e.g., Figures 16 to 18 and Figures 30 to 32.

not provide for additional personnel in hypothermic conditions. Therefore, it assumed that hypothermic conditions would be a factor in response efficiency.

The National Weather Service issues a “Freezing Spray Advisory” when freezing water droplets accumulate at rate of less than 0.8 inches per hour, which corresponds to moderate icing (National Weather Service, 2006). Once icing conditions begin to occur, there is little that can be done to prevent the icing and still allow for recovery operations. Therefore, the onset of moderate icing conditions is considered a response limit.

Figure 7. Wind chill chart (NOAA, 2006).

Temperature (°F)

Wind (mph) \ Calm	40	35	30	25	20	15	10	5	0	-5	-10	-15	-20	-25	-30	-35	-40	-45
5	36	31	25	19	13	7	1	-5	-11	-16	-22	-28	-34	-40	-46	-52	-57	-63
10	34	27	21	15	9	3	-4	-10	-16	-22	-28	-35	-41	-47	-53	-59	-66	-72
15	32	25	19	13	6	0	-7	-13	-19	-26	-32	-39	-45	-51	-58	-64	-71	-77
20	30	24	17	11	4	-2	-9	-15	-22	-29	-35	-42	-48	-55	-61	-68	-74	-81
25	29	23	16	9	3	-4	-11	-17	-24	-31	-37	-44	-51	-58	-64	-71	-78	-84
30	28	22	15	8	1	-5	-12	-19	-26	-33	-39	-46	-53	-60	-67	-73	-80	-87
35	28	21	14	7	0	-7	-14	-21	-27	-34	-41	-48	-55	-62	-69	-76	-82	-89
40	27	20	13	6	-1	-8	-15	-22	-29	-36	-43	-50	-57	-64	-71	-78	-84	-91
45	26	19	12	5	-2	-9	-16	-23	-30	-37	-44	-51	-58	-65	-72	-79	-86	-93
50	26	19	12	4	-3	-10	-17	-24	-31	-38	-45	-52	-60	-67	-74	-81	-88	-95
55	25	18	11	4	-3	-11	-18	-25	-32	-39	-46	-54	-61	-68	-75	-82	-89	-97
60	25	17	10	3	-4	-11	-19	-26	-33	-40	-48	-55	-62	-69	-76	-84	-91	-98

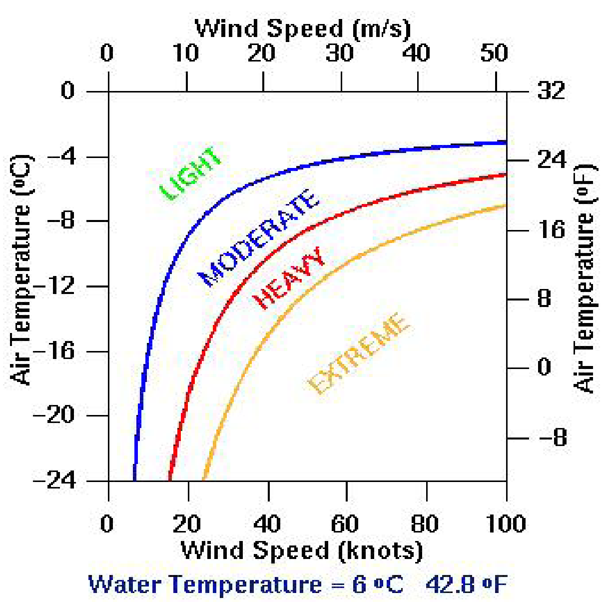
Frostbite Times: 30 minutes, 10 minutes, 5 minutes

$$\text{Wind Chill (°F)} = 35.74 + 0.6215T - 35.75(V^{0.16}) + 0.4275T(V^{0.16})$$

Where, T= Air Temperature (°F) V= Wind Speed (mph)

Effective 11/01/01

Figure 8. Plot of icing predictions based on air temperature and wind speed for a water temperature of 42.8 °F (Naval Postgraduate School, 2006).



Based on the information presented in Figures 7 and 8, the following response limits for air temperature were used for the Response Gap analysis:

- Green: Effect is minimal or absent. Temperatures above 26º F, or otherwise as not covered in the yellow or red conditions.
- Yellow: Response operations possible but impaired. Temperatures between 25º F and 17º F when wind speed exceeds 10 knots.
- Red: Response operations not possible or effective. Temperature 16º F.

VISIBILITY

Poor visibility can hamper or preclude a response by limiting the ability to track and encounter oil slicks; it is also an important response safety consideration. Darkness and poor visibility also affect vessel navigation, the helmsmen's ability to see and anticipate on-coming seas, the crew's ability to work on deck, and the ability to recover a man overboard. Lighting equipment may be used to maintain position and help oil spill response/recovery efforts to continue once a spill has been sighted and spill operations begun in daylight/visible conditions.

Infrared technologies and artificial lighting can aid oil tracking in low visibility conditions, but these technologies are not specified in the tactical description in the C-plan and to our knowledge have not been routinely drilled or practiced. The RMROL section of the C-plan states that depending on other environmental factors, the visibility limitation for vessels tracking oil may occur when visibility is less than 0.5 nautical miles.

Reduced visibility can be caused by fog, rain, snow, and darkness. During the review of the Methods Report for this study, there was discussion about the reliability of marine observations for visibility estimates. It was decided to use darkness, as determined by civil twilight, as the only data for determining visibility. Visibly restrictions due to fog, low clouds, and precipitation have not been considered because of difficulties in standardizing their measurement.

Based on the C-plan, the following response limits for visibility were used:

- Green: Effect is minimal or absent. Visibility greater than 0.5 nautical miles.
- Yellow: Response operations possible but impaired. Visibility between 0.25 and 0.5 nautical miles, including darkness.
- Red: Response operations not possible or effective. Visibility less than 0.25 nautical miles.

But, since the only data used to determine visibility is darkness, these limits were simplified to:

- Green: Effect is minimal or absent. Daylight.
- Yellow: Response operations possible but impaired. Darkness.

Response Gap Index

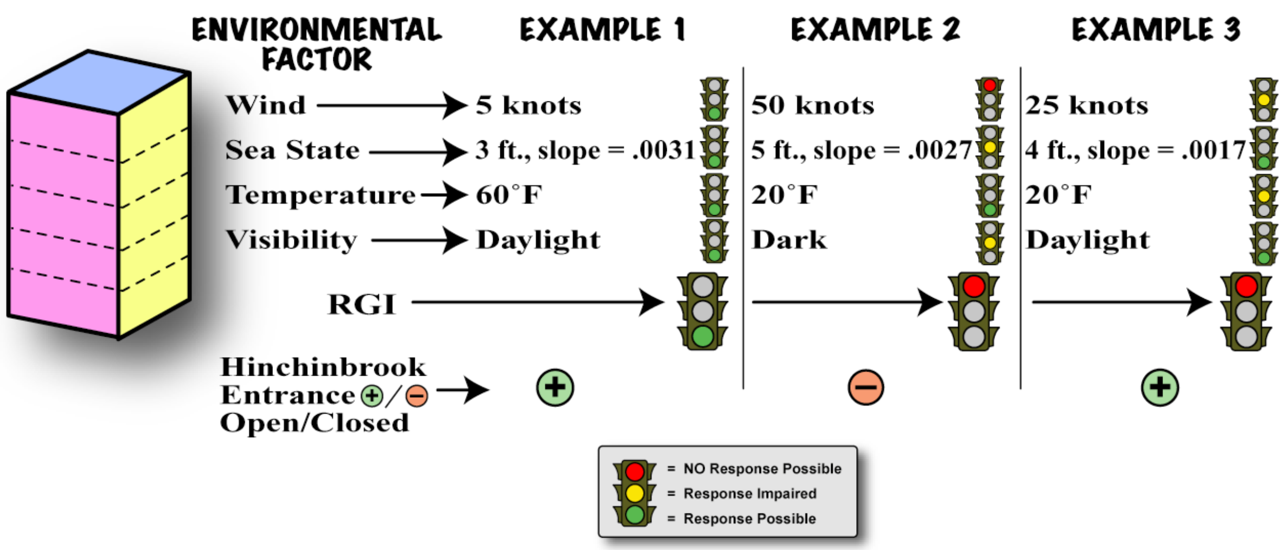
Finally, a Response Gap Index (RGI) was computed for each observational period based on a rule that addresses the interaction of the environmental factors. RGI was recorded as either Green (response possible) or Red (response not possible/ effective). *Since an RGI will only be computed for observational periods when Hinchinbrook Entrance is open, the tabulation and analysis of the Red RGI will result in a reasonable estimate of the Response Gap.*

The RGI was computed as follows:

1. If any environmental factor is ruled Red, RGI = Red,
2. If all environmental factors are ruled Green, RGI = Green,
3. If only one environmental factor is ruled Yellow and the remainder are ruled Green, RGI = Green, and
4. If two or more factors are ruled Yellow, RGI = Red.

Figure 9 shows how this process works.

Figure 9. An example of how a RGI rule might be applied.



Results

This section presents the results of the Response Gap Index analysis. Environmental factors are characterized for the two selected operating areas: Central PWS and Hinchinbrook Entrance.

An analysis of the hourly wind and wave height observations from the data buoy at Hinchinbrook Entrance showed that closure conditions at Hinchinbrook Entrance occurred only 1.7% of the time from 2000 through 2005. These observations and the concurrent observations for Central PWS were excluded from the data sets upon correlating the conditions within PWS to conditions at Hinchinbrook Entrance up to the closure threshold. That is, the determination of the Response Gap Index was for those conditions when Hinchinbrook Entrance was still open to outbound laden tanker traffic.

However, in this presentation of the environmental factors data, data points taken when Hinchinbrook Entrance was closed are included because they constituted only 1.7% of the observations.

Central PWS Operating Area

CHARACTERIZATIONS OF ENVIRONMENTAL FACTORS

Figure 10 shows the monthly maximum wind gust and wind speed and Figure 11 presents a histogram and cumulative-probability curve for wind speeds in Central PWS. Note that the average wind speed is 10.6 knots, the median is 8.9 knots, and the most probable value is between 4 and 6 knots.

Figure 10. Maximum wind speed and wind gust by month for Central PWS, 2000-2005. *Note: Error bars show one standard deviation of monthly value.*

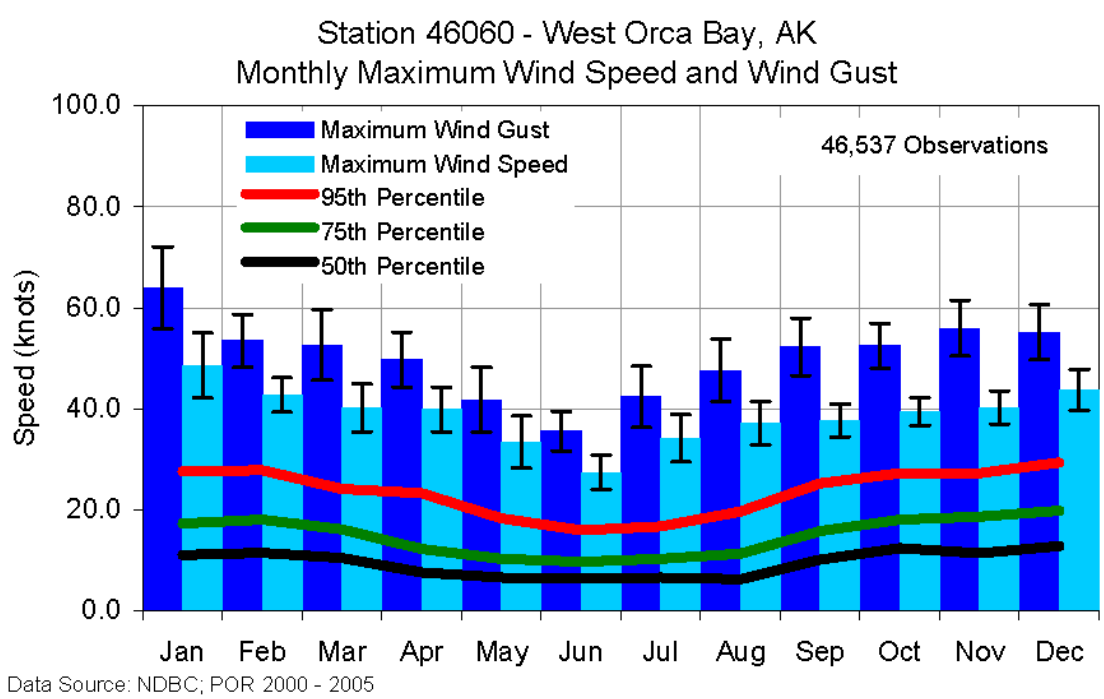


Figure 11. Histogram and cumulative probability of wind speed for Central PWS, 2000-2005.

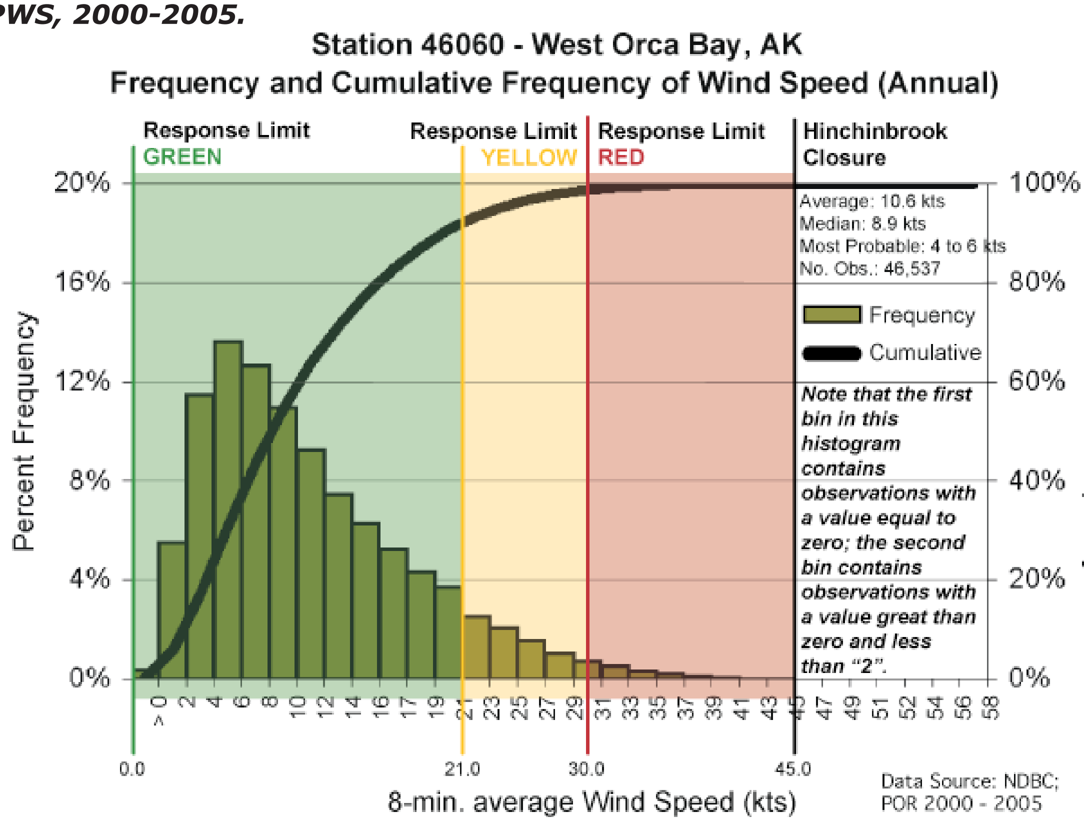


Figure 12 presents a histogram of wind directions. The most probable wind direction is from 90° to 105° (0° corresponds to winds arriving from true North). Figure 13 presents a histogram and cumulative-probability curve of wind gusts in Central Prince William Sound.

Figure 12. Histogram of wind direction for Central PWS, 2000-2005.

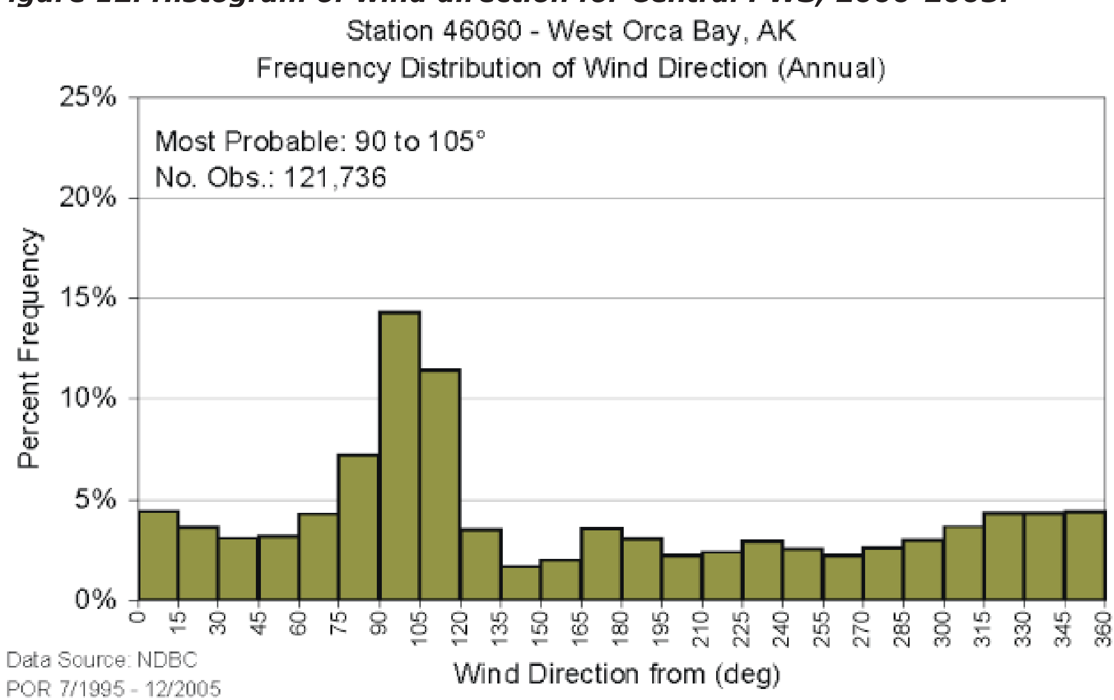


Figure 13. Histogram and cumulative probability of wind gust for Central PWS, 2000-2005.

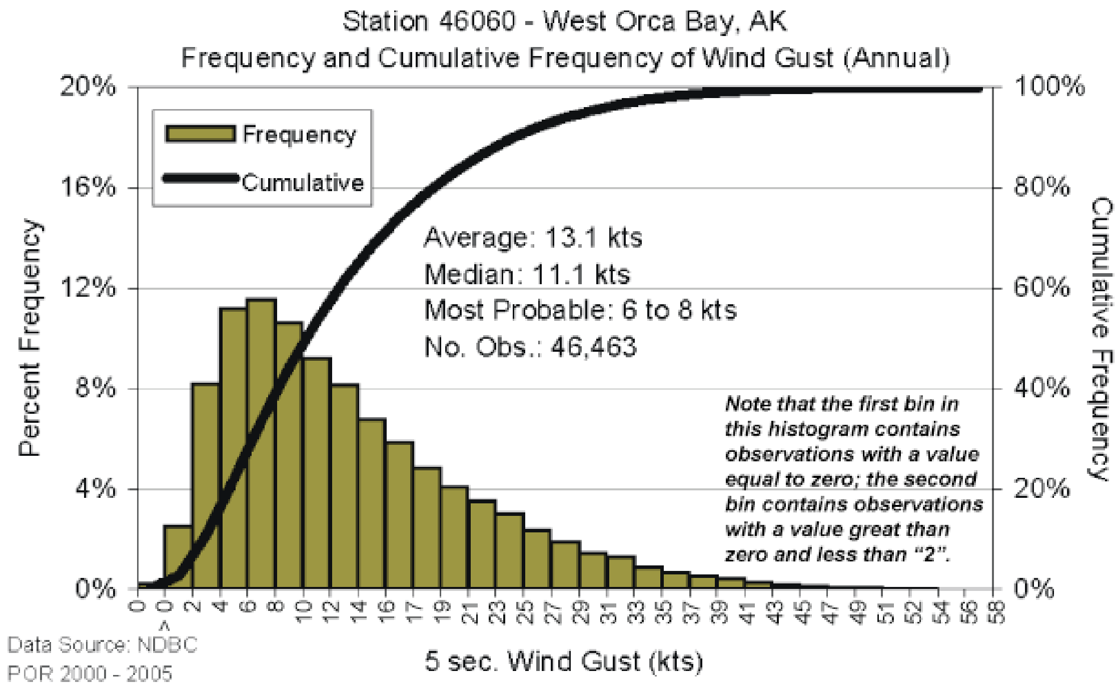


Figure 14 shows the monthly maximum significant wave height and Figure 15 presents a histogram and cumulative-probability curve for significant wave heights in Central PWS. Note that the average significant wave height is 2.23 feet, the median is 1.8 feet, and the most probable value is between 0.82 and 1.64 feet.

Figure 14. Monthly maximum significant wave height for Central PWS, 2000-2005. *Note: Error bars show one standard deviation of monthly value.*

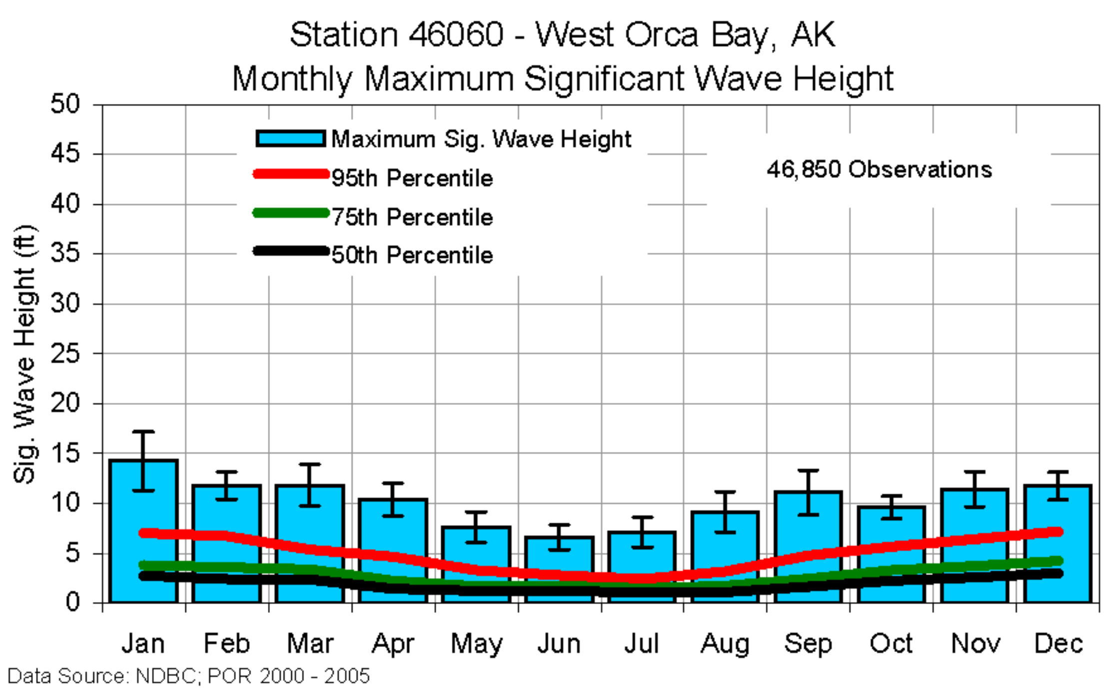
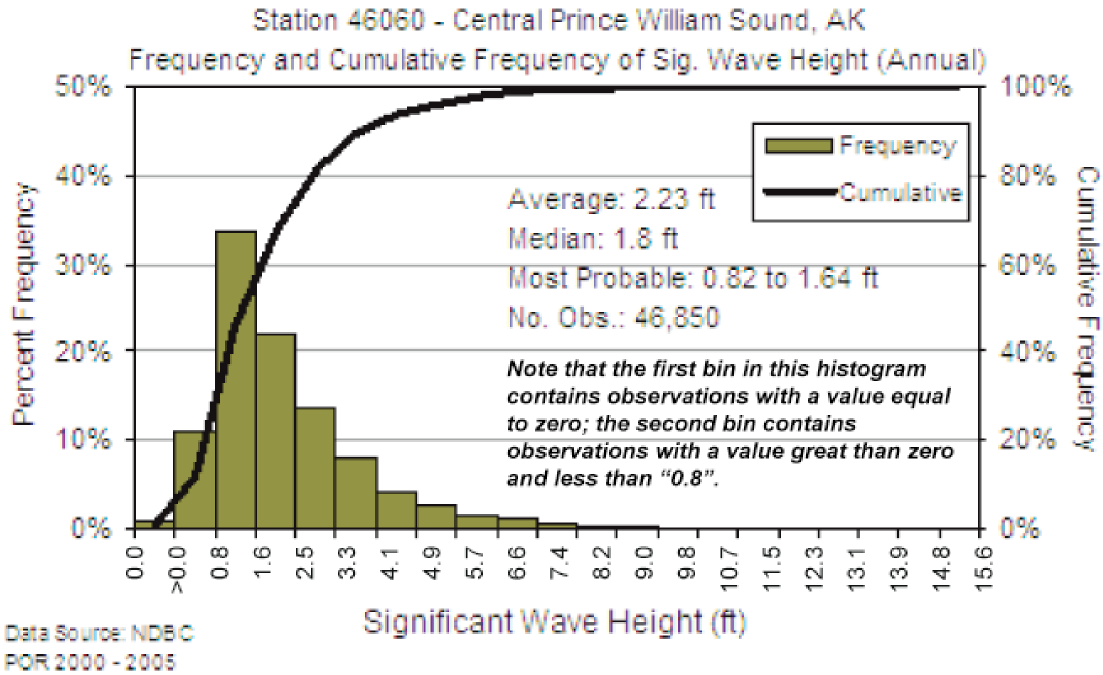


Figure 15. Histogram and cumulative probability of significant wave height for Central PWS, 2000-2005.



The annual joint probability distribution of significant wave height and modal wave period for Central Prince William Sound is presented in Figure 16 on the following page; the same data presentation for summer and winter are shown in Figures 17 and 18, respectively. Curves corresponding to wave steepness parameter thresholds between swell, wind waves, and very steep waves are indicated in the figure. The plot shows the presence of clearly defined wind, wave, and swell regimes.

Figure 16. Annual joint probability of significant wave height and modal period for Central PWS, 2000-2005.

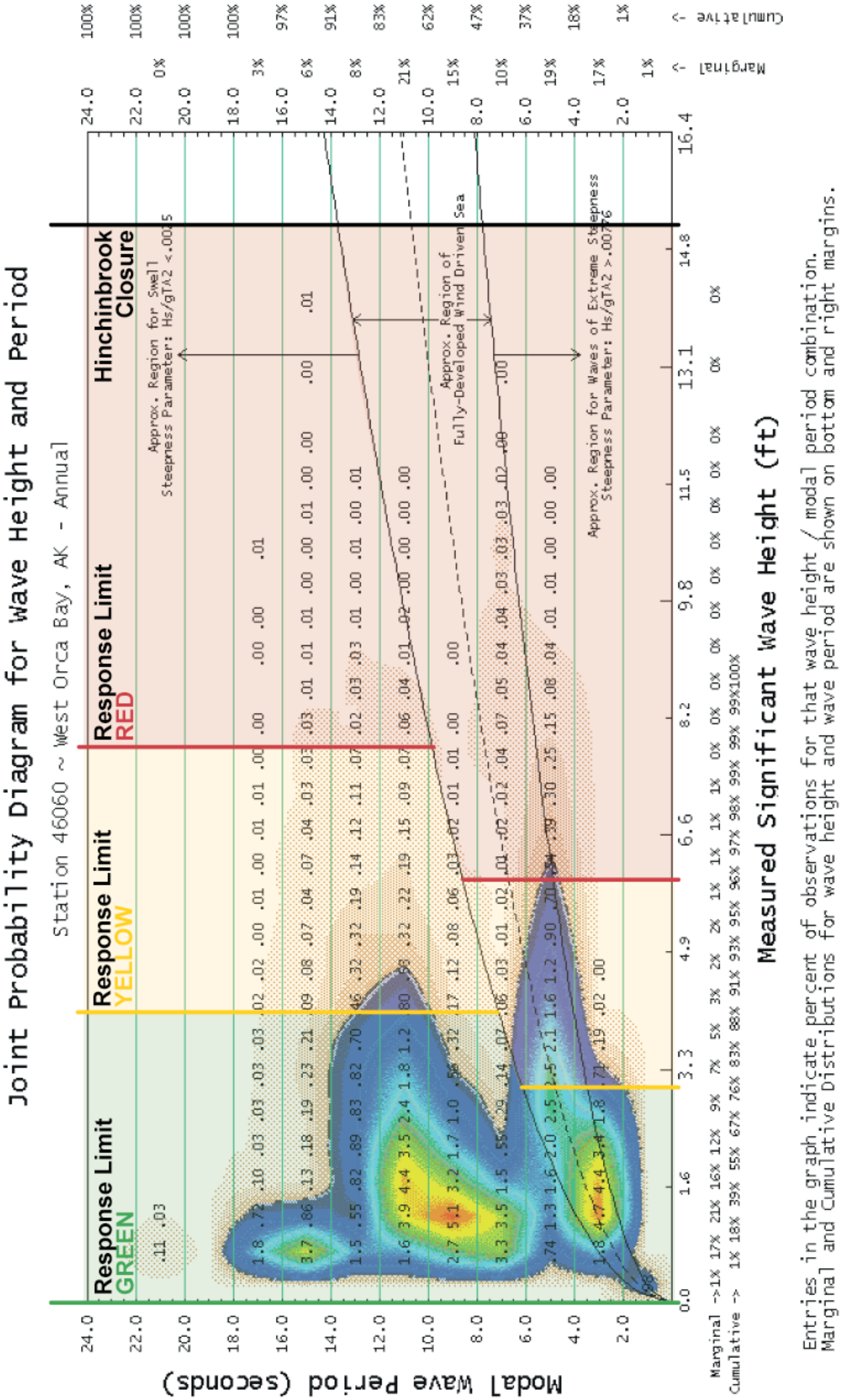


Figure 17. Summer joint probability of significant wave height and modal period for Central PWS, 2000-2005.

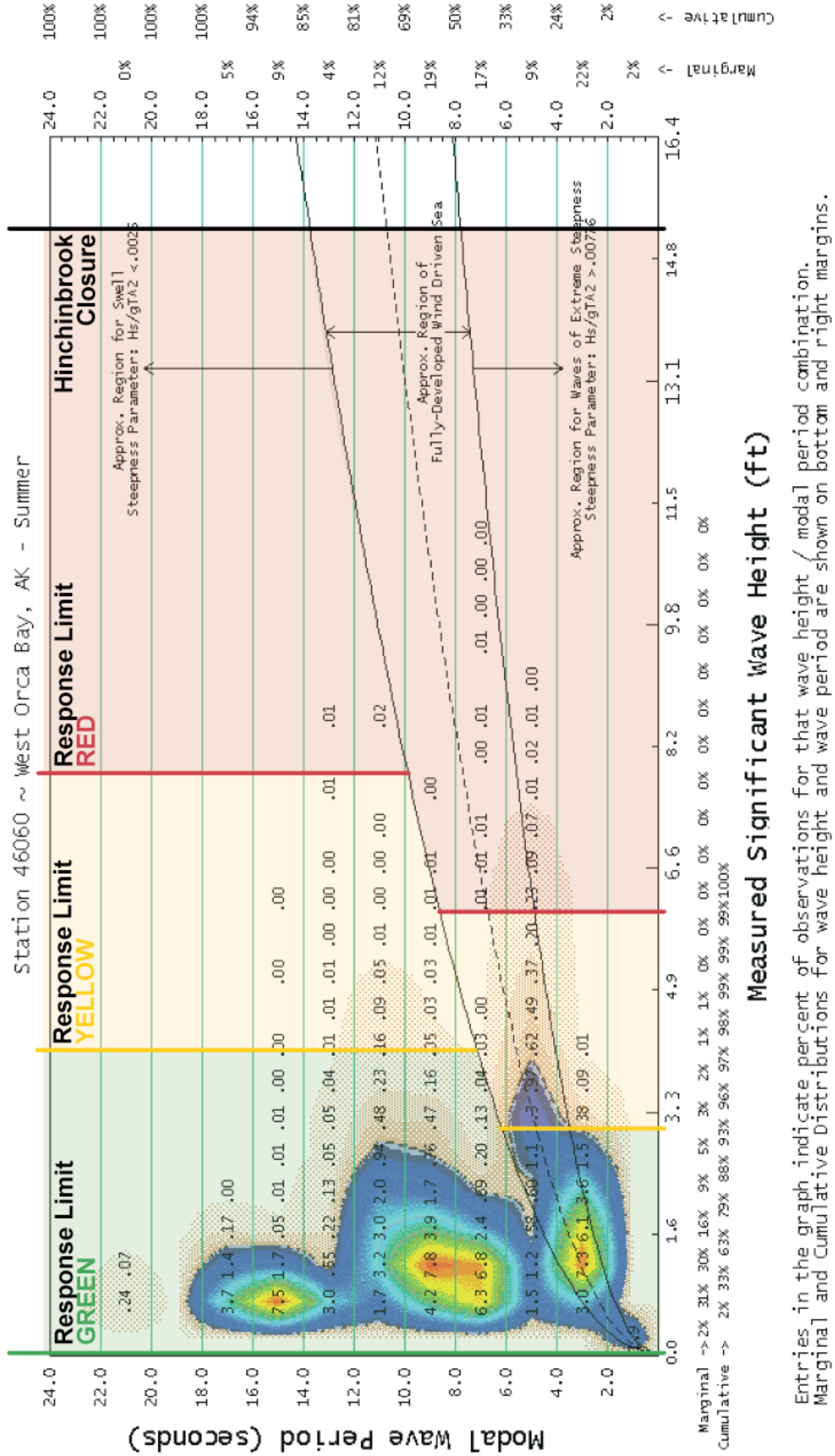


Figure 18. Winter joint probability of significant wave height and modal period for Central PWS, 2000-2005.

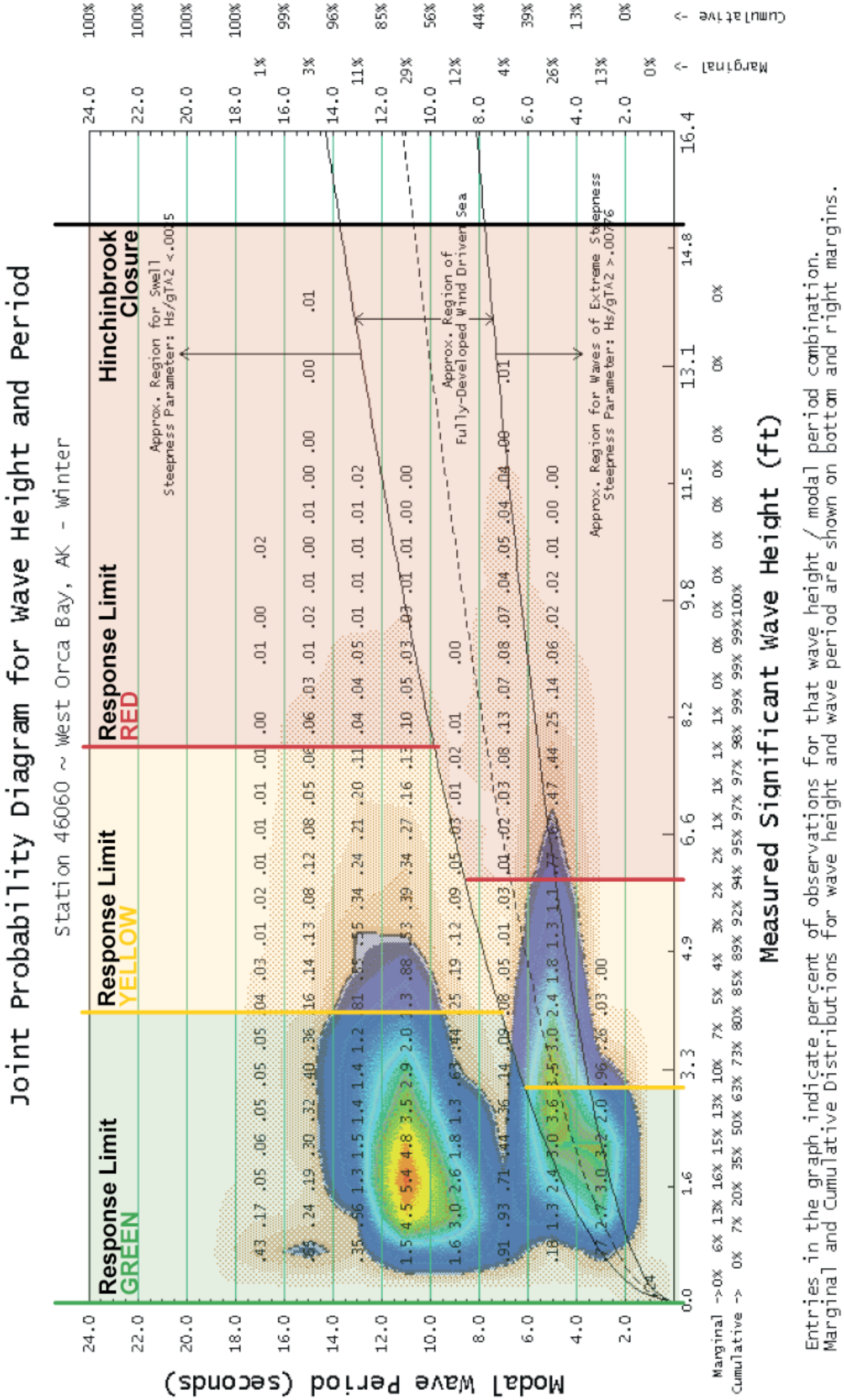


Figure 19 shows monthly maximum, minimum, and mean air temperature and Figure 20 presents a histogram and cumulative-probability curve for air temperatures in Central Prince William Sound. Note that the average air temperature is 45.1°F, the median is 44.2°F, and the most probable value is between 36 and 39°F.

Figure 19. Maximum, minimum, and mean air temperature by month for Central PWS, 2000-2005. *Note: Error bars show one standard deviation of monthly value.*

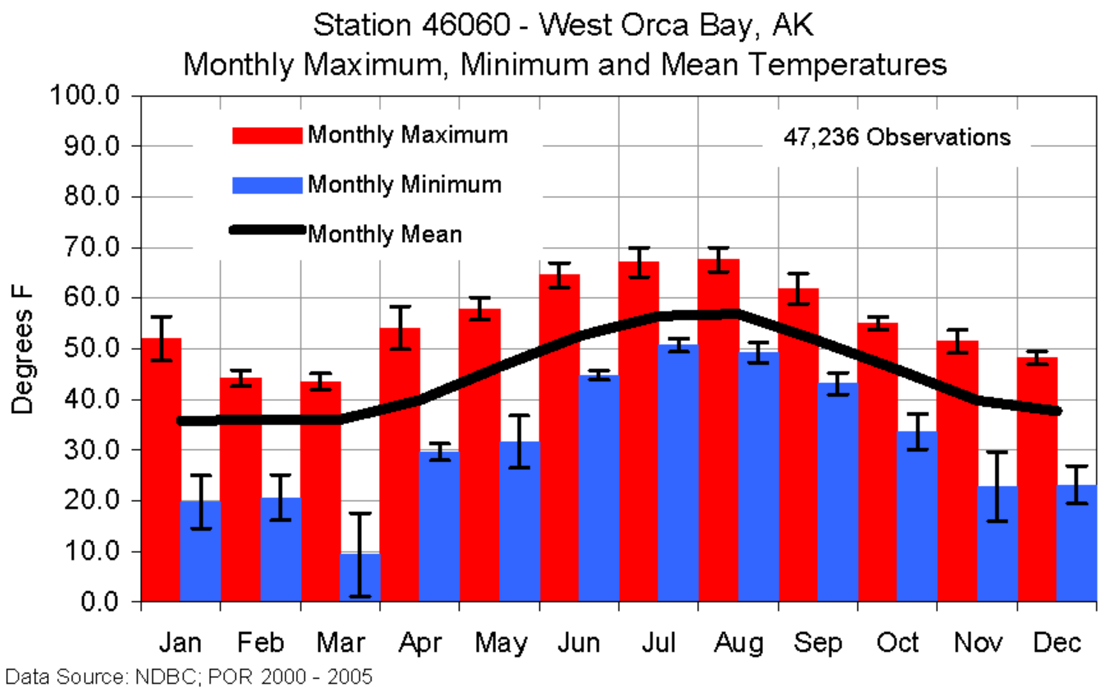


Figure 20. Histogram and cumulative probability of air temperature for Central PWS, 2000-2005.

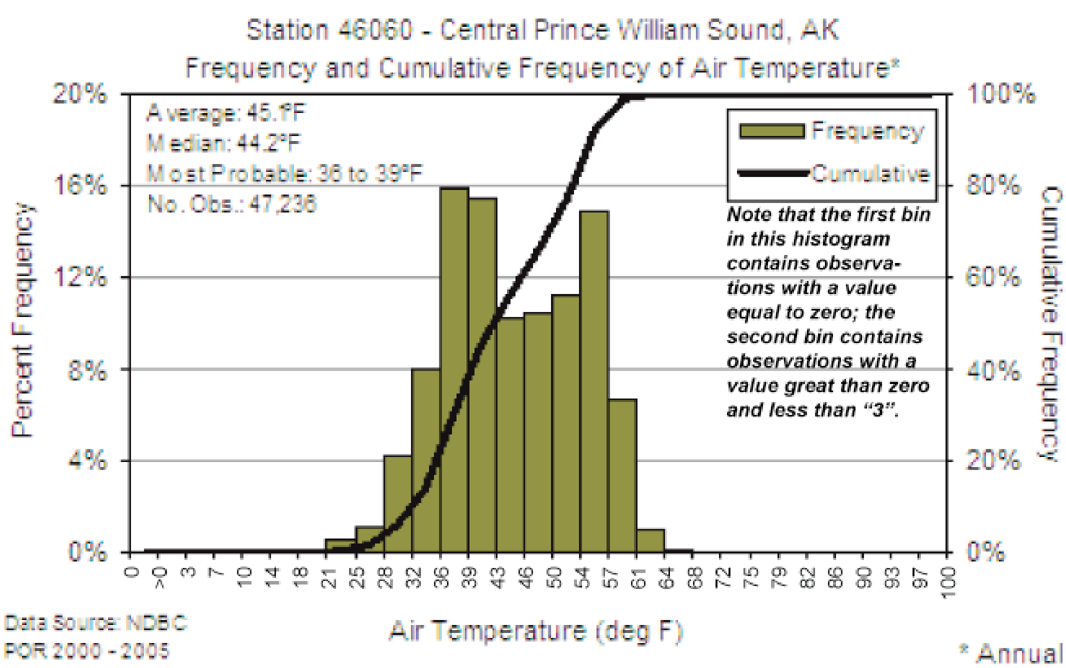
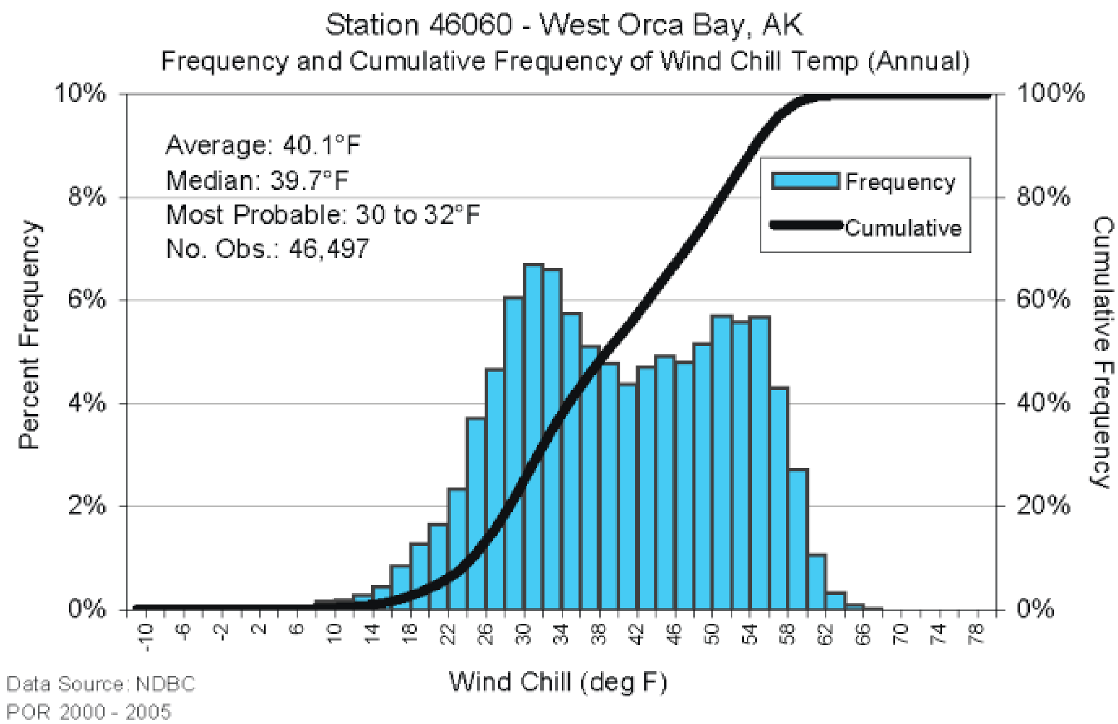


Figure 21 presents a histogram and cumulative-probability curve for wind chill in Central Prince William Sound. Note that the average wind chill is 40.1°F, the median is 39.7°F, and the most probable value is between 30 and 32°F.

Figure 21. Histogram and cumulative probability of wind chill for Central PWS, 2000-2005.



Figures 22 and 23 present daylight curves for Valdez and Cordova respectively, representing Central Prince William Sound. The curves are based on civil-twilight data obtained from the U.S. Naval Observatory. The daylight/darkness data are purely astronomical and, as such, do not include any variations due to topography or weather. The curves show that there are, for example, about 6 hours of darkness and 18 hours of daylight on May 1. Valdez is at higher latitude than Cordova and has slightly more daylight in the summer. This is reflected in the figures.

Figure 22. Daylight curves for Valdez, Alaska, representing the upper limits of daylight for Central PWS, 2000-2005.

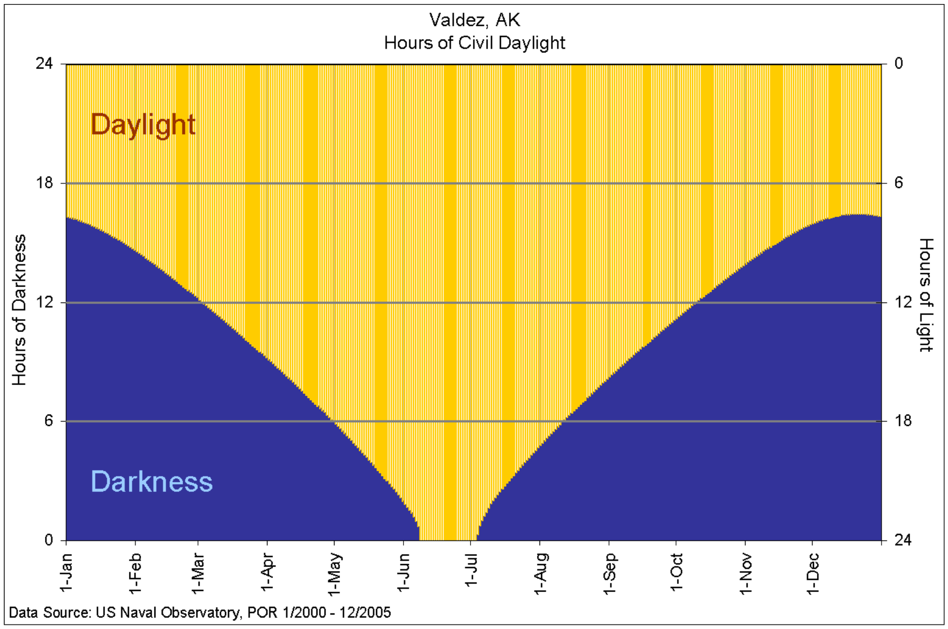
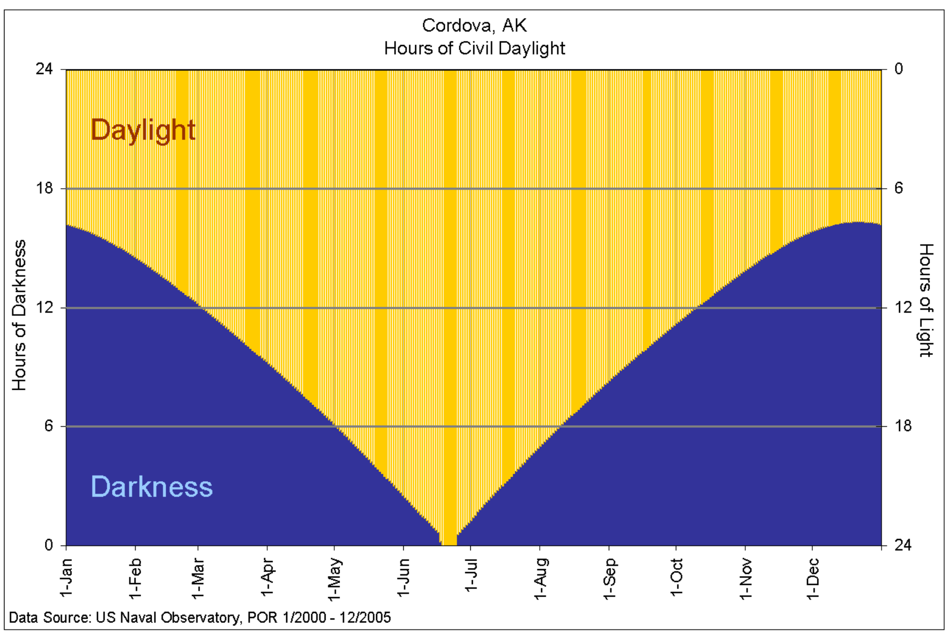


Figure 23. Daylight curves for Cordova, Alaska, representing the lower limits of daylight for Central PWS, 2000-2005.



RESPONSE GAP

Table 7 presents the results of applying the response operating limits[25] to the dataset for the West Orca Bay Buoy 46060 in Central PWS for those times when Hinchinbrook Entrance was computed to be open. When each factor was considered individually, the response limits were rarely exceeded. Sea state only exceeded the operating limits 1.6% of the time and wind exceed the limits only 1.0% of the time. Sea state was categorized as yellow, meaning response effectiveness was diminished, 13.7% of the time. Wind was categorized as yellow 7.8% of the time, and visibility due to darkness was categorized as yellow 37.5 % of the time. Air temperature was almost always within the green category, 99.7% of the time.

Table 7: Results of applying response limits to environmental observations taken from West Orca Bay Buoy 46060 in Central PWS when Hinchinbrook Entrance was open.[26]

Environmental Factor	Green	Yellow	Red
Wind	91.2%	7.8%	1.0%
Sea State	84.7%	13.7%	1.6%
Air Temperature	99.7%	0.3%	< 0.1%
Visibility	62.5%	37.5%	n/a

Table 8 presents the results of computing the Response Gap Index for the West Orca Bay Buoy 46060 dataset in Central PWS. When the environmental factors are considered together, the response limitations are exceeded 12.6% of the time. The response limits are exceeded more in winter, 23.1% of the time, than in summer, 4.2% of the time. Almost 90.0% of the red RGI were due to two or more yellow conditions. Of those, almost 75% included a yellow condition due to darkness.

Table 8: Results of applying Response Gap Index rule to environmental observations taken from West Orca Bay Buoy 46060 in Central PWS when Hinchinbrook Entrance was open.

Season	Green	Red
Entire Year	87.4%	12.6%
Summer (April through September)	95.8%	4.2%
Winter (October through March)	76.9%	23.1%

25 The response operating limits are listed in Table 5.

26 An analysis of wind and wave data at Hinchinbrook Entrance revealed that closure conditions were reached at Hinchinbrook Entrance only about 1.7% of the time during 2000 to 2005 (inclusive).

Hinchinbrook Operating Area

CHARACTERIZATIONS OF ENVIRONMENTAL FACTORS

Figure 24 shows the monthly maximum wind gust and wind speed and Figure 25 presents a histogram and cumulative-probability curve for wind speeds at Hinchinbrook Entrance. Note that the average wind speed is 13 knots, the median is 11.5 knots, and the most probable value is between 6 and 8 knots.

Figure 24. Maximum wind speed and wind gust by month for Hinchinbrook Entrance, 2000-2005. *Note: Error bars show one standard deviation of monthly value.*

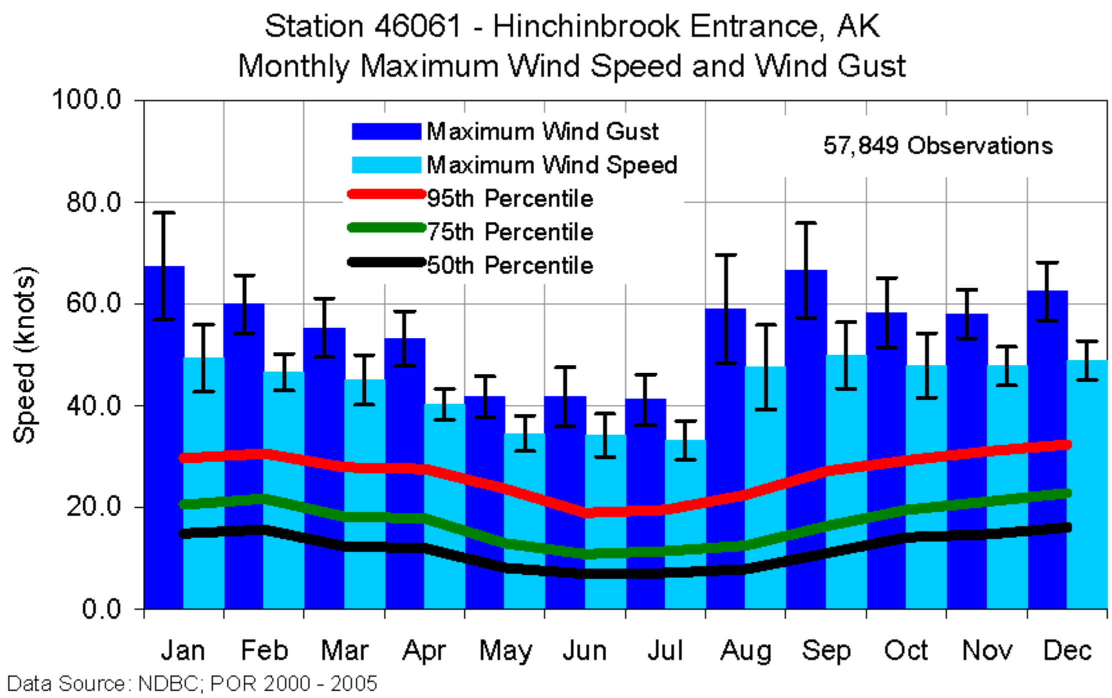


Figure 25. Histogram and cumulative probability of wind speed for Hinchinbrook Entrance, 2000-2005.

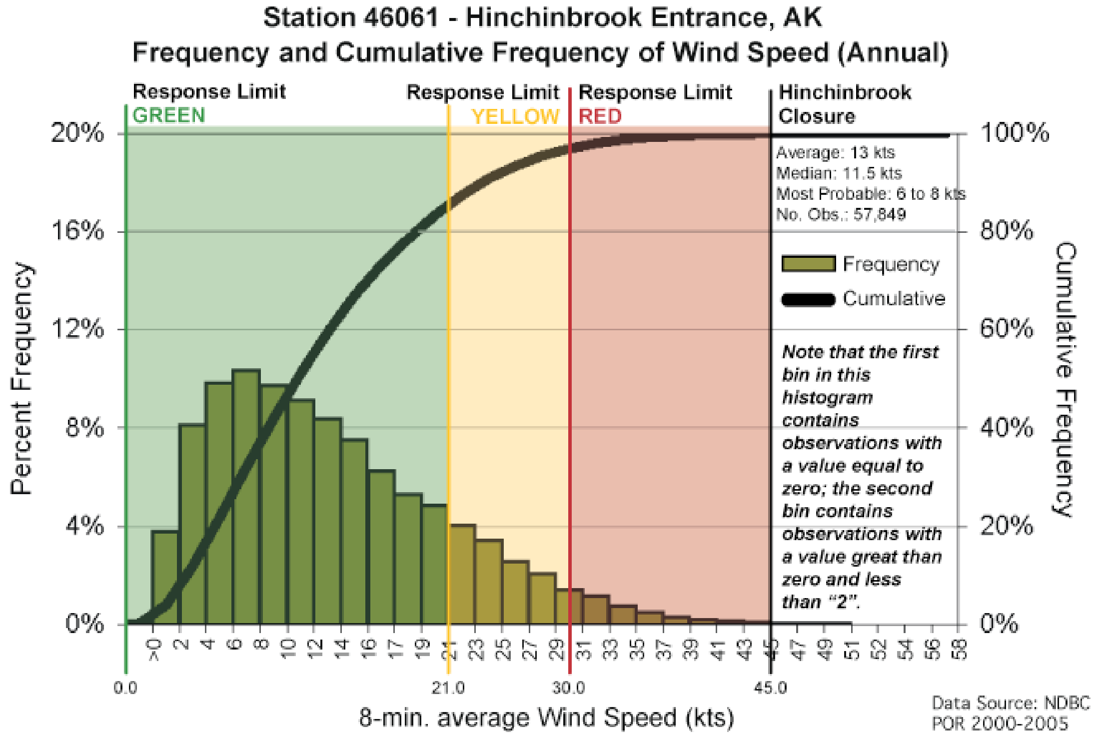


Figure 26 presents a histogram of wind directions. The most probable wind direction is from 75° to 90° (0° corresponds to winds arriving from true North). Figure 27 presents a histogram and cumulative-probability curve of wind gusts at Hinchinbrook Entrance.

Figure 26. Histogram of wind directions for Hinchinbrook Entrance, 2000-2005. *Note: Error bars show one standard deviation of monthly value.*

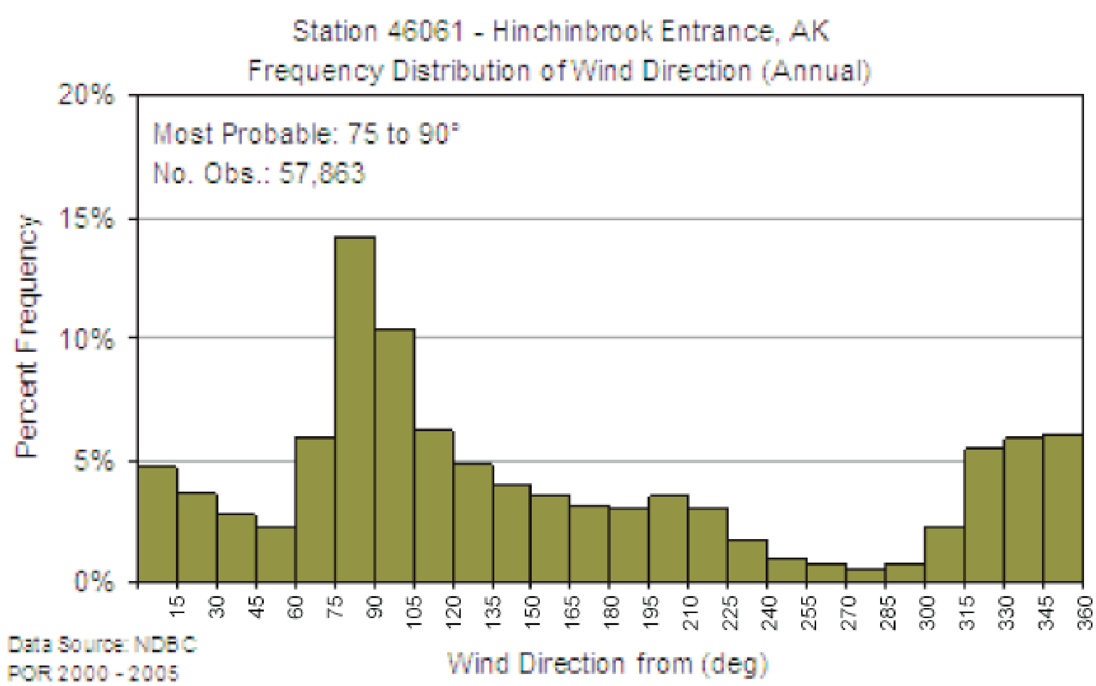


Figure 27. Histogram and cumulative probability of wind gust for Hinchinbrook Entrance, 2000-2005.

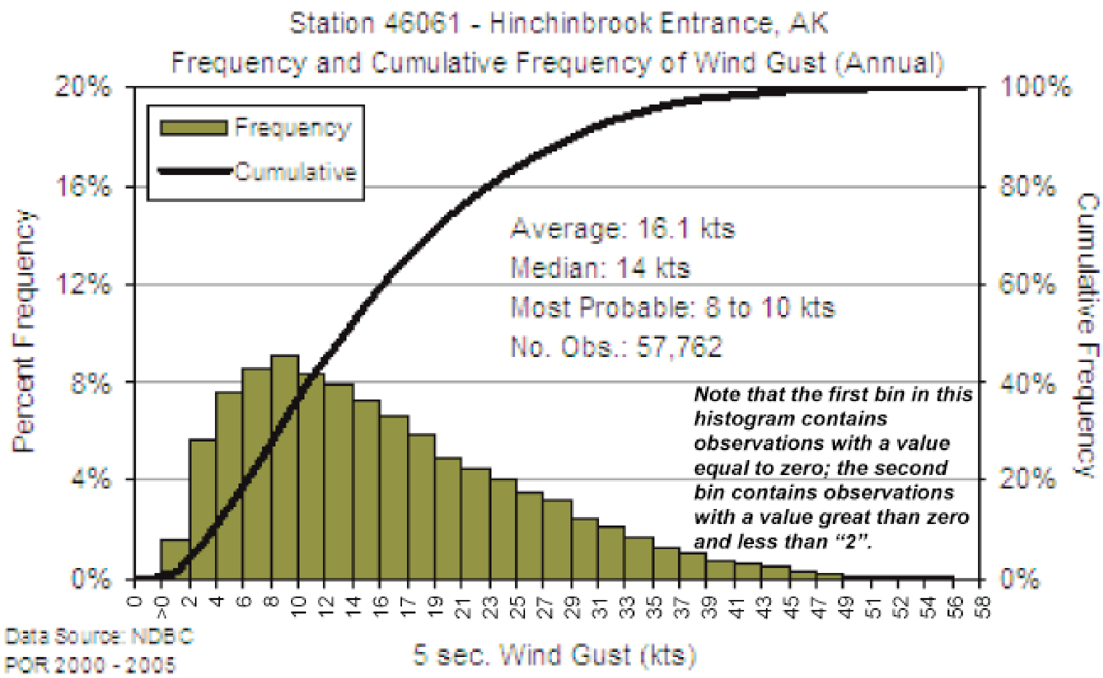


Figure 28 shows the monthly maximum significant wave height and Figure 29 presents a histogram and cumulative-probability curve for significant wave heights at Hinchinbrook Entrance. Note that the average significant wave height is 5.2 feet, the median is 4.2 feet, and the most probable value is between 1.64 and 2.46 feet.

Figure 28. Maximum significant wave height by month for Hinchinbrook Entrance, 2000-2005. *Note: Error bars show one standard deviation of monthly value.*

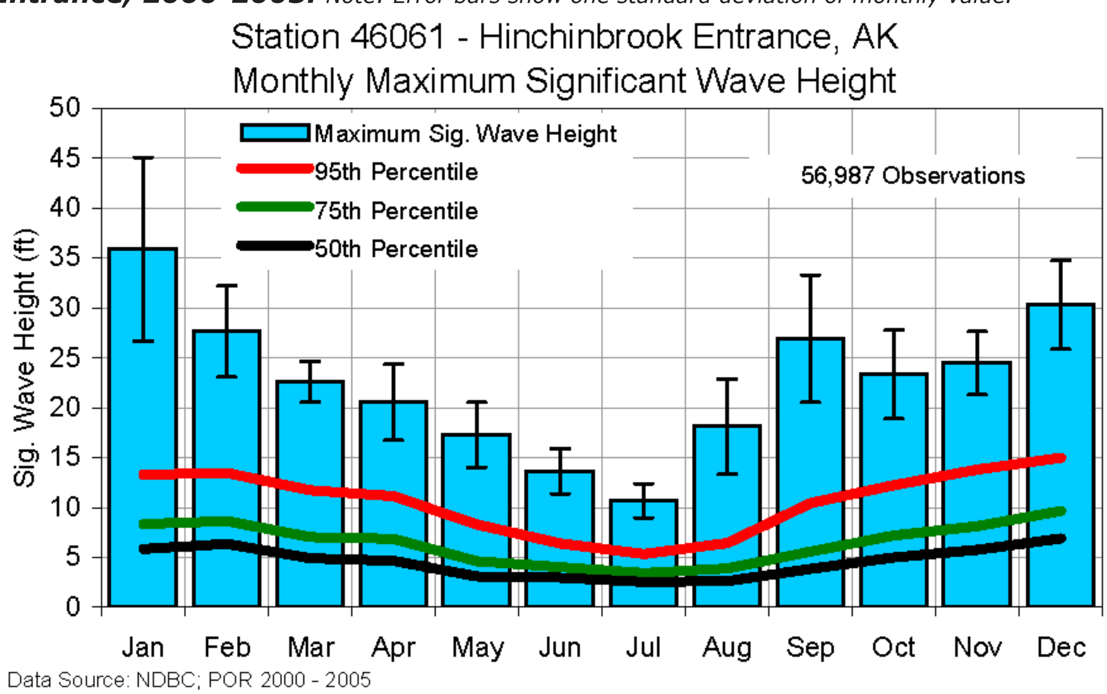
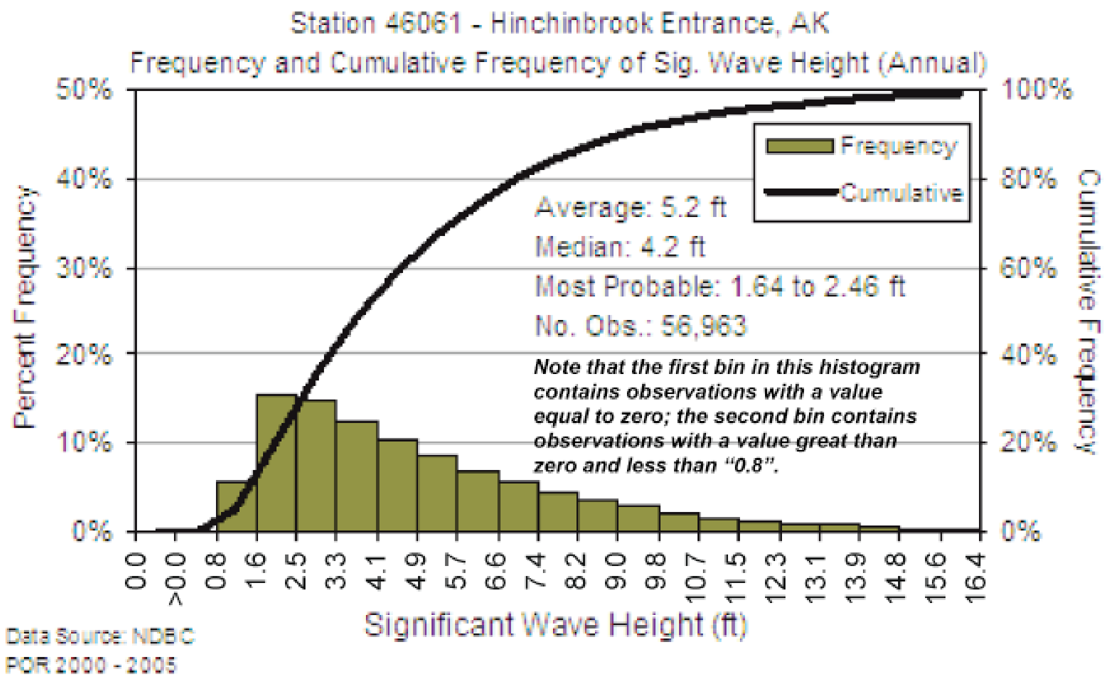


Figure 29. Histogram and cumulative probability of significant wave height for Hinchinbrook Entrance, 2000-2005.



The annual joint probability distribution of significant wave height and modal wave period for Hinchinbrook Entrance is presented in Figure 30 below ; the same data presentation for summer and winter are shown in Figures 31 and 32, respectively. Curves corresponding to wave steepness parameter thresholds between swell, wind waves, and very steep waves are indicated in the figure. In contrast to the evident delineation between wind wave and swell regimes for Central PWS (Figure 16), Figure 29 shows that swell predominates in Hinchinbrook Entrance and the wave heights are also significantly larger.

Figure 30. Annual joint probability distribution of significant wave height and modal wave period for Hinchinbrook Entrance, 2000-2005.

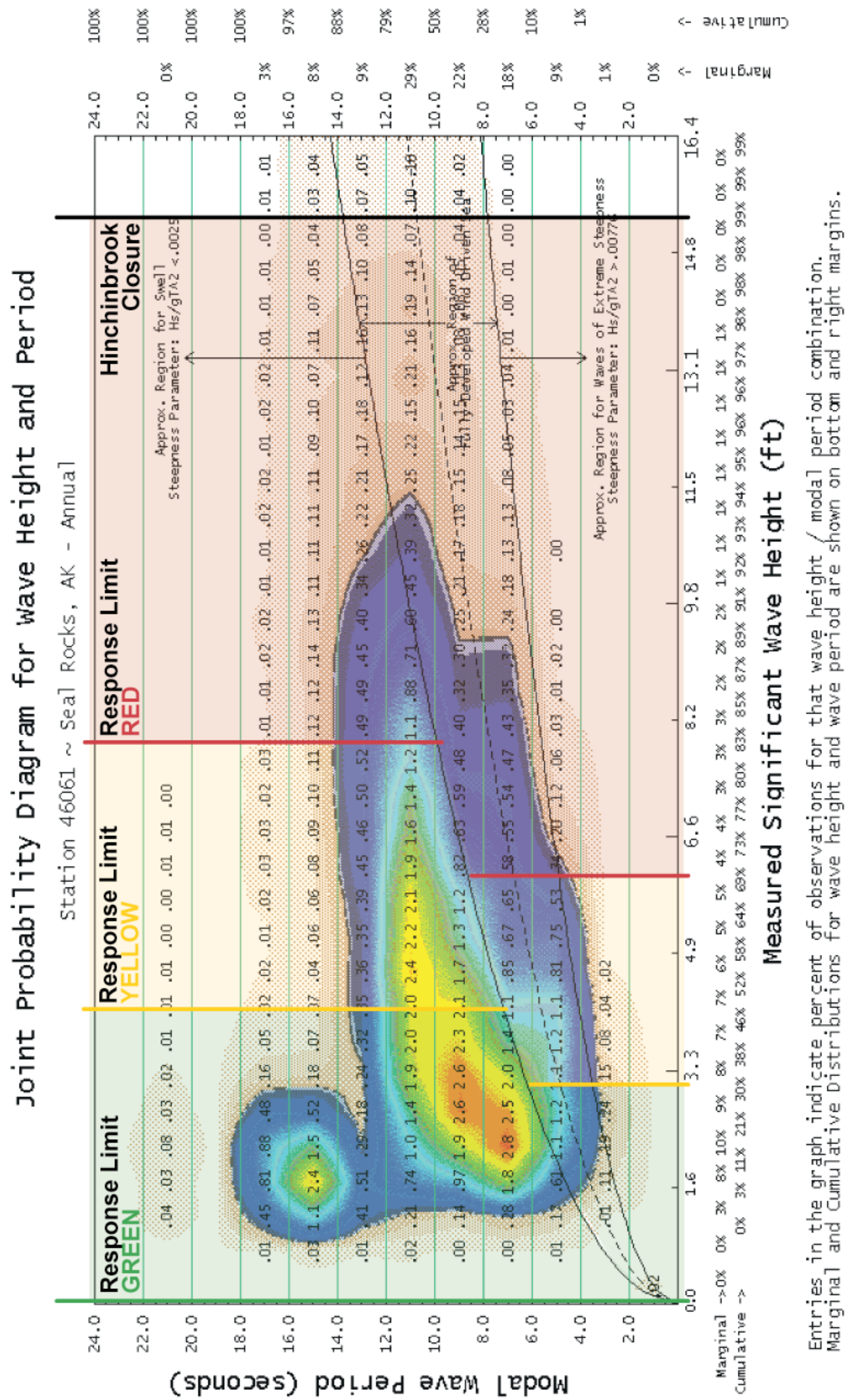


Figure 31. Summer joint probability distribution of significant wave height and modal wave period for Hinchinbrook Entrance, 2000-2005.

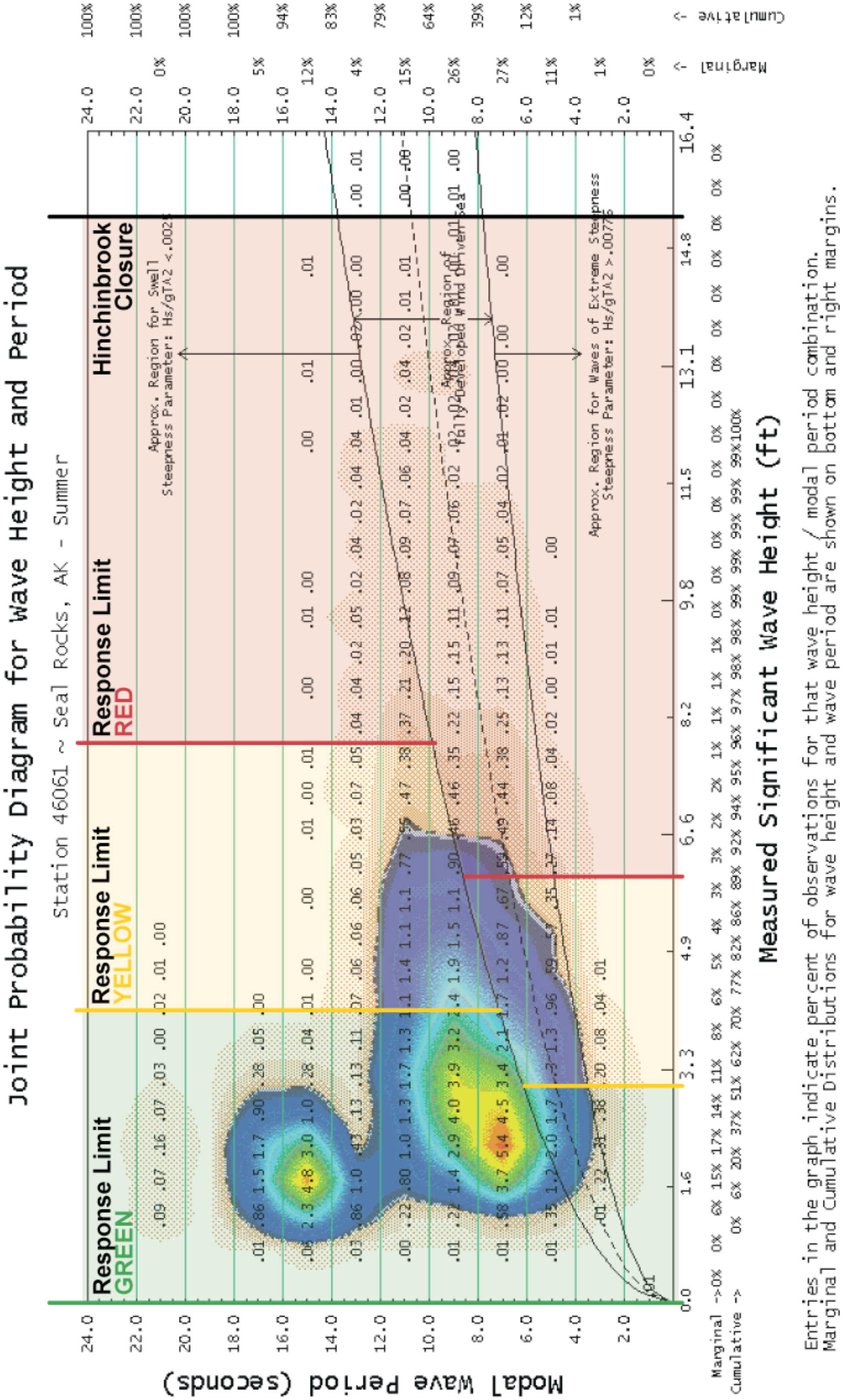


Figure 32. Winter joint probability distribution of significant wave height and modal wave period for Hinchinbrook Entrance, 2000-2005.

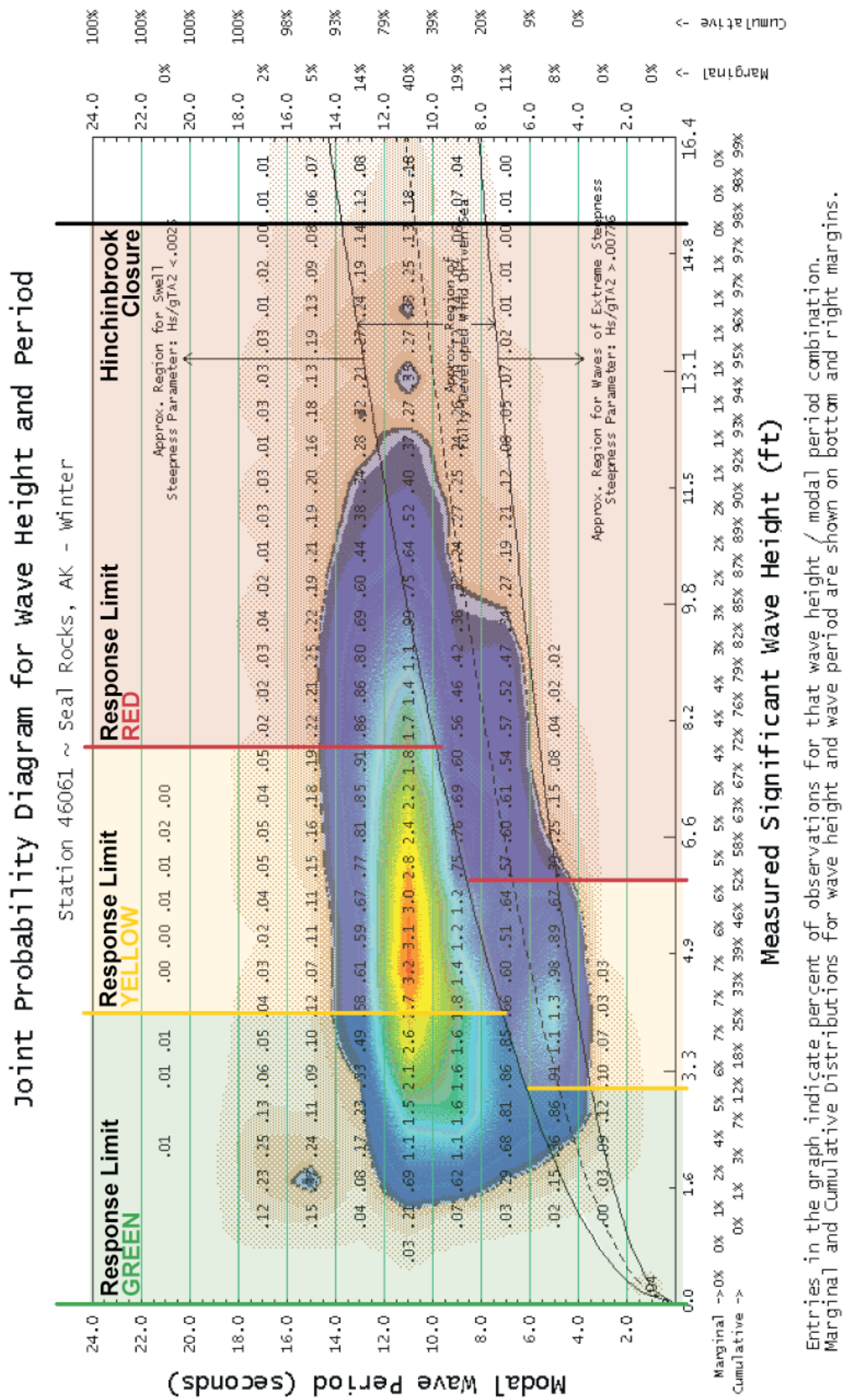


Figure 33 shows monthly maximum, minimum, and mean air temperature and Figure 34 presents a histogram and cumulative-probability curve for air temperatures at Hinchinbrook Entrance. Note that the average air temperature is 44.1°F, the median is 43°F, and the most probable value is between 39 and 43°F.

Figure 33. Maximum, minimum, and mean air temperature by month for Hinchinbrook Entrance, 2000-2005.

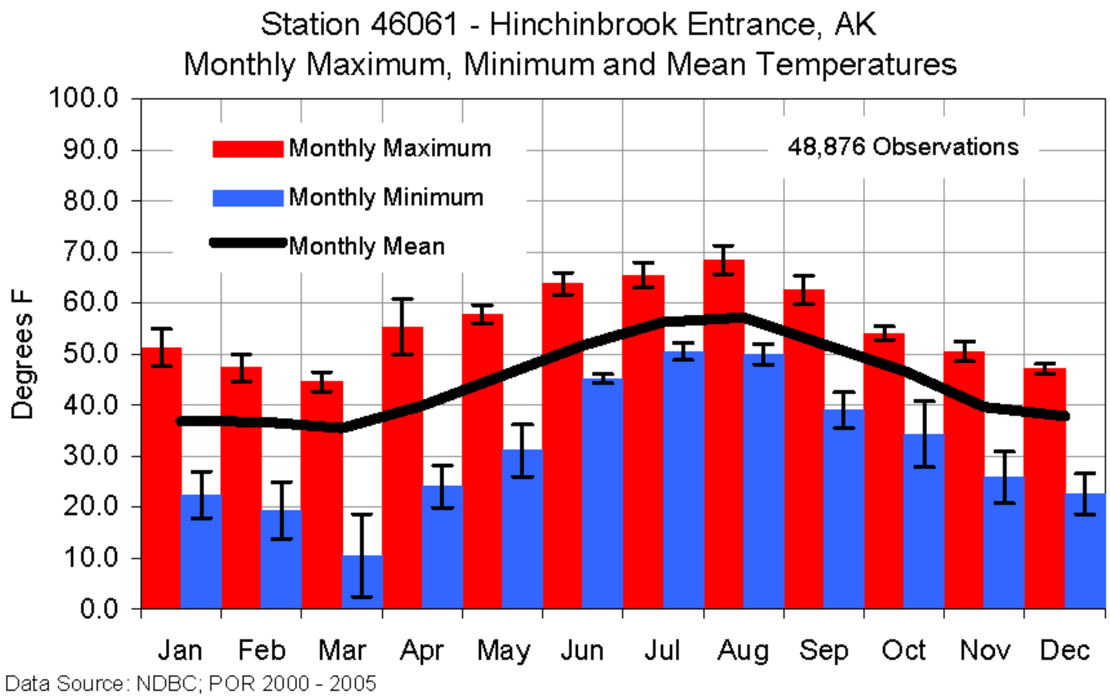


Figure 34. Histogram and cumulative probability of air temperature for Hinchinbrook Entrance, 2000-2005.

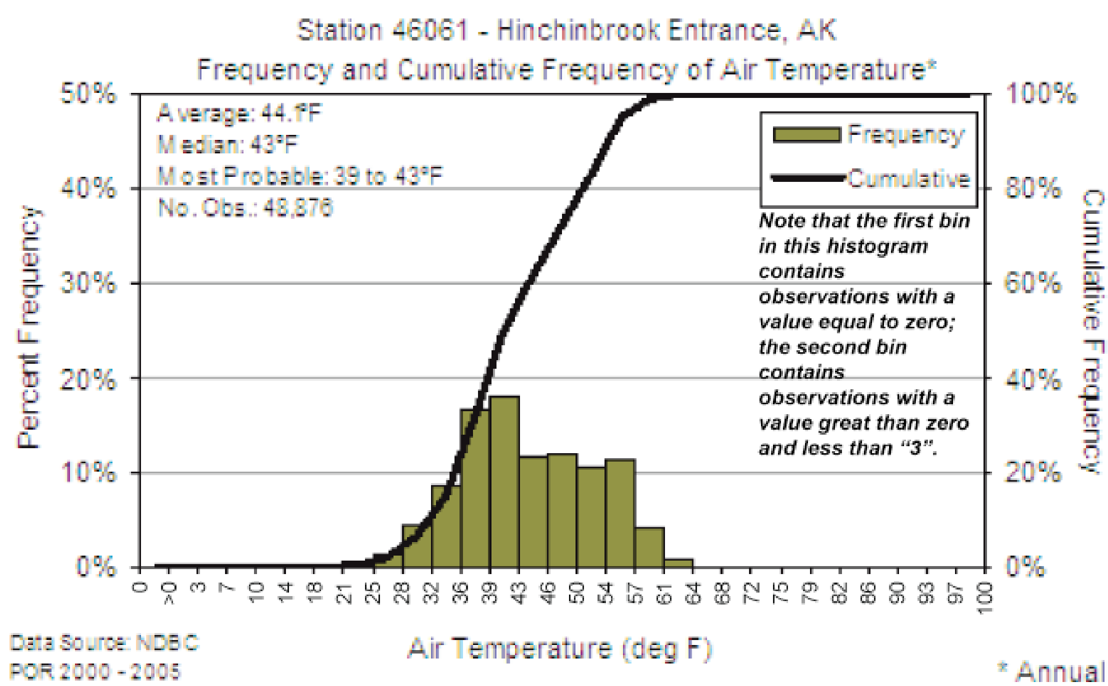


Figure 35 presents a histogram and cumulative-probability curve for wind chill at Hinchinbrook Entrance. Note that the average wind chill is 37.6°F, the median is 36.3°F, and the most probable value is between 30 and 32°F.

Figure 35. Histogram and cumulative probability of wind chill for Hinchinbrook Entrance, 2000-2005.

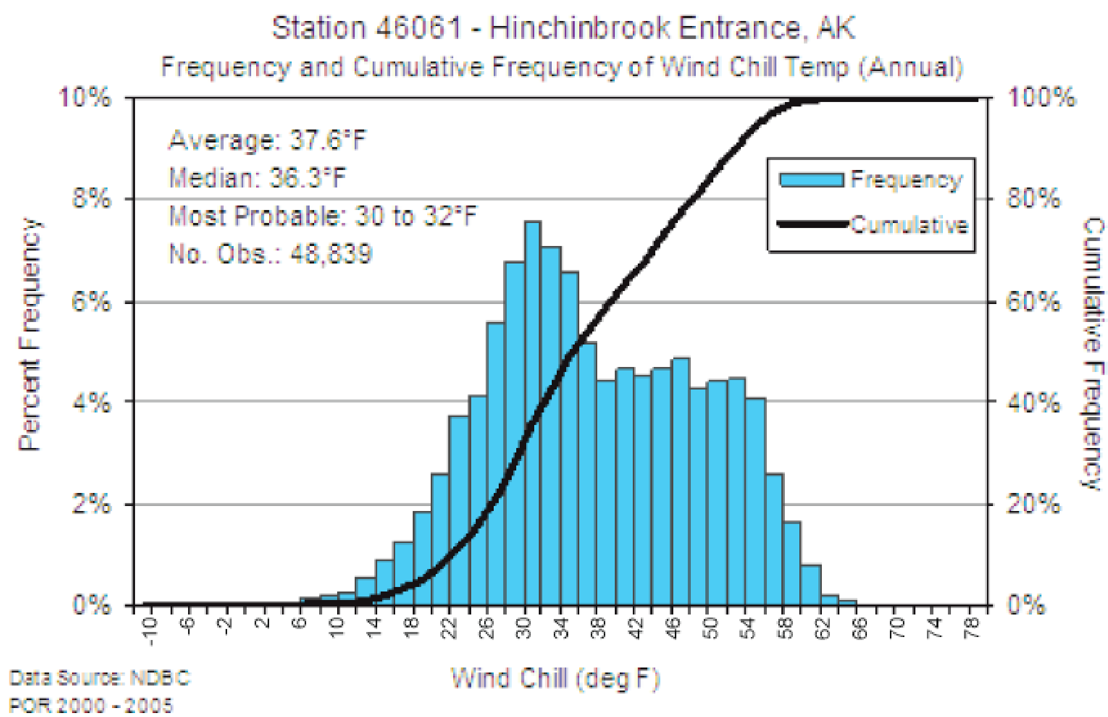
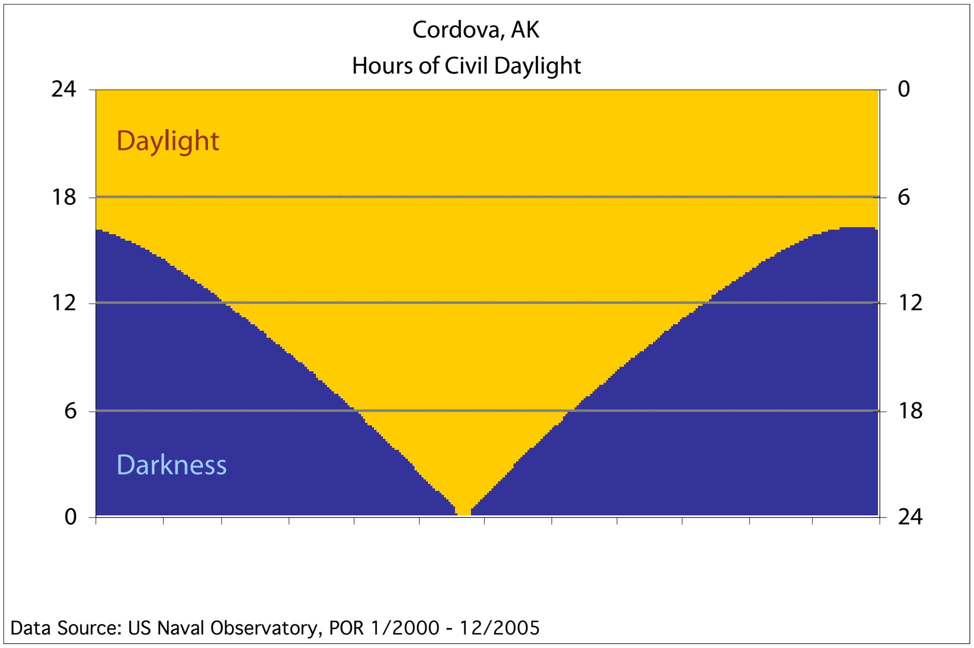


Figure 36 presents daylight curves for Cordova, representing Hinchinbrook Entrance. It shows that there are, for example, about 6 hours of darkness and 18 hours of daylight on May 1.

Figure 36. Daylight curve for Cordova, Alaska, representing Hinchinbrook Entrance, 2000-2005.



RESPONSE GAP

Table 9 presents the results of applying the response operating limits[27] to the dataset for the Seal Rocks Buoy 46061 at Hinchinbrook Entrance when it was computed to be open. When each factor is considered individually, the response limits were seldom exceeded. Sea state exceeded the operating limits 19.2% of the time and wind exceeded the limits only 2.9% of the time. Sea state was categorized as yellow, meaning response effectiveness was diminished, 34.6% of the time. Wind was categorized as yellow 13.5% of the time, and visibility due to darkness was categorized as yellow 37.5 % of the time. Air temperature was almost always within the green category, 99.5% of the time.

27 The response operating limits are listed in Table 5.

Table 9: Results of applying response limits to environmental observations taken from Seal Rocks Buoy 46061 at Hinchinbrook Entrance when the Entrance was open.

Environmental Factors	Green	Yellow	Red
Wind	83.6%	13.5%	2.9%
Sea State	46.2%	34.6%	19.2%
Air Temperature	99.5%	0.5%	< 0.1%
Visibility	62.5%	37.5%	n/a

Table 10 presents the RGI results at Hinchinbrook Entrance when the environmental factors are considered together. In this case, the response limitations are exceeded 37.7% of the time. The response limits are exceeded more in winter, 65.4% of the time, than in summer, 15.6% of the time. Almost 60.0% of the red RGI were due to two or more yellow conditions. Of those, almost 88% included a yellow condition due to darkness.

Table 10: Results of applying Response Gap Index rule to environmental observations taken from Seal Rocks Buoy 46061 at Hinchinbrook Entrance when the Entrance was open.

Season	Green	Red
Entire Year	62.6%	37.7%
Summer (April through September)	84.4%	15.6%
Winter (October through March)	35.4%	65.4%

Response Gap Index Across Both Operating Areas

Table 11 presents the results of considering the RGI in both operating areas simultaneously. For any given observation, if the RGI for either the West Orca Bay Buoy (Central PWS) or Seal Rocks Buoy (Hinchinbrook Entrance) was computed as red, then the accumulated RGI was assessed as red.

When both operating areas were considered together, the response limitations were exceeded 38.5% of the time. Response limitations were exceeded more in winter, 66.1% of the time, than in summer at 16.2% of the time. The aggregate results are very similar to the Seal Rocks Buoy results, as there were few times (~ 2%) when the West Orca Bay Buoy RGI was red when the Seal Rocks Buoy RGI was not. Usually, a red RGI condition for this aggregate is caused by unfavorable conditions in the Hinchinbrook operating area.

Table 11: Aggregate Response Gap Index for both operating areas.

Season	Green	Red
Entire Year	61.5%	38.5%
Summer (April through September)	83.8%	16.2%
Winter (October through March)	33.9%	66.1%

Discussion

Limitations of this Study

Accurately quantifying the Response Gap is a challenge because data are scarce and the determination of response limits is inherently subjective. A hindcast of 6 years of observations from known data sources that reflect actual past conditions in two of the operating areas in PWS was used to estimate the Response Gap. Use of this data to predict present and future conditions assumes that future conditions will be similar. However, some scientists predict that storms will increase, bringing more frequent high winds, high sea states, and low visibility (McCarthy et. al., 2001).

While the observations used in this study reflect actual conditions at the location of the data buoys, and we believe they are by and large reflective of conditions in their respective operating areas, we acknowledge that conditions can and do vary from the buoy locations even within the same operating area. This is true in both the Hinchinbrook Entrance and Central Prince William Sound operating areas. In the Hinchinbrook Entrance operating area actual conditions in the narrows at the entrance can vary significantly from the Seal Rock buoy's location due to tidal currents and exposure to williwaw winds from Port Etches.[28] The West Orca Bay Buoy is influenced by easterly winds from Orca Bay and conditions elsewhere in the Central Prince William Sound operating area can be quiet different. Any mariner knows that visibility, wind, and sea state can change dramatically over short distances and time spans due to many factors, including currents, topography and bathymetry.

The only visibility limitation considered for this analysis was daylight vs. darkness. Visibility limitations due to fog and precipitation were not considered, but could pose a substantial challenge to response effectiveness. Thus, the percentage of time when the RGI was calculated as red would certainly increase if more visibility data were considered.

There is some evidence that the NDBC buoys may actually under report wind and sea state. One researcher reported the following:

> *"As has been noted by marine forecasters in the Anchorage office for years, moored buoys tend to under report the sustained winds when wind speeds and sea heights get large. The question as to whether the sustained wind or wind gusts that are reported by buoys are more representative as to the actual conditions experienced by mariners has become a larger question as products to verify marine forecasts against the buoys have become routinely issued. It is the belief of the forecasters and management of the Anchorage forecast office that winds should be verified against a buoy's wind gust speed instead of the sustained wind speed.*

28 The Seal Rocks Buoy 46061 is located approximately 4.3 nautical miles south-southwest of the center of Hinchinbrook Entrance.

> *As winds increase and seas build, errors in the sustained wind speed become prominent. This appears to be caused by two major factors - both of them influenced by eight minutes that wind speeds are averaged over to produce the sustained wind. The first is the amount of time the buoy spends in the wave trough as seas get large. When the buoy is spending a significant part of it's eight minutes in the trough of the wave, the wind is partially blocked by the wave and the speed consequently diminishes. Another factor is buoy tipping as the waves propagate through it. Especially when the wave period is short and waves are steep, the buoy bends over in relationship to the horizon. Since the anemometer is no longer perpendicular to the surface wind, it's reported speed is reduced. Both of these problems become significant as wind speeds and sea heights increase." (Zingone, E., 2004).*

The two buoys used in the Response Gap analysis use a standard anemometer located five meters above the sea surface and report the wind speed averaged over eight minutes. Gusts are measured for a five second interval. The normal time interval for measuring sustained winds at a land station is two minutes. A thirty degree tipping of the buoy would cause a 13% under reporting of the wind speed.

Under-reporting of sea conditions can also occur. This is due in large part to the 20-minute interval used to average the wave characteristics. The reported number is the average of the highest one-third of all wave heights recorded during the 20-minute interval. This is quite accurate when the waves are a consistent swell or wind-wave. The under-reporting arises when there are both swells and wind-waves of significant height and different periods. When peaks coincide with peaks, or troughs with troughs the seas build. When peaks coincide with troughs it dampens the seas. When the swells and wind-waves are from different directions this can create very confused seas. The long recording period may mask the presence of a few larger waves by a preponderance of smaller ones.

The response limits chosen for this study are intended to apply only to the openwater mechanical recovery system deploying the Tactic O-1 described in the PWS Tanker C-plan. More specifically, this study only applies to the equipment configuration assumptions described earlier in this report, especially the use of large seiners as boom towing vessels. Smaller fishing vessels or workboats would have lower limits, which would increase the Response Gap estimates Other recovery systems and tactics would yield different results.

Quantifying Response System Limitations

The response system limits used in this analysis are based largely on best professional judgment because no one in the public arena is collecting the kind of information that would allow quantitative evaluations on response operating limits. Despite the large number of drills, exercises, and actual responses that have been conducted in the past 15 years, very little data has been collected on the effects of weather, sea state, and other factors on any response system/tactic. Such data would be extremely valuable in conducting Response Gap analyses.

One possible method to quantify response system limitations would be to conduct field tests in varying environmental conditions near the NOAA buoys. The buoy instrumentation would be used to capture environmental conditions and a panel of observers could be used to rate the effectiveness of the response system/tactic and note the cause and nature of any ineffectiveness. A database of the results of such deployments would greatly increase the accuracy of the Response Gap estimates.

Since deploying the response system in conditions that approach the limits of response would raise safety concerns, modeling could be used to predict the effect of more severe conditions on the vessels, equipment, and personnel. Models can accurately predict the amount of deck wetness and motion a particular sea state would cause for any given vessel.

Improving Environmental Factor Data Collection

One finding from our work to date is that the environmental data is sparse in many areas. There have been many improvements in environmental monitoring in the past few years with the advent of relatively cheap telemetry systems. Still, more data is needed, particularly on sea state and visibility. Observations from vessels promise to provide valuable information, especially in operating areas where no NOAA buoy exists.

Lowering the Response Gap

The Response Gap can be decreased either by lowering the closure limits or increasing the capability of the response system, or both. There were 42,066 valid hourly observations in the combined dataset for the West Orca Bay and Seal Rocks buoys. Only 710 (1.7%) of these hourly observations met or exceeded at least one of the closure conditions. If the closure limits matched the Response Gap limits (wind speed = 30 knots and wave height = 6 feet), then 12,289 hourly observations (29.3%) would exceed one or more of the closure conditions. Obviously, closing PWS's oil transportation system 30% of the time would seriously impact the ability to operate the Trans-Alaska Pipeline and the Valdez Marine Terminal, especially since the closures would occur most often during the winter months.

Increasing response capability might be accomplished in a number of different ways. The most cost effective way to increase response capability may be to improve and demonstrate ways to track and recover oil in darkness. More robust recovery equipment, such as the large boom systems used in the North Sea, might also increase response capability but would also require a similar increase in towboat capability. It is difficult to evaluate ways to increase response capability until a quantitative approach is used to evaluate response limitations. This can be accomplished through field tests and modeling.

Recommendations

Upon conclusion of the PWS Response Gap study, Nuka Research and Planning Group makes the following recommendations to the RCAC.

1. **QUANTIFY RESPONSE LIMITATIONS**

   Better quantification of response limits would significantly improve Response Gap measurements. This can be done by field tests and modeling discussed above. We recommend that the RCAC initiate a project with SERVS and the Response Planning Group (RPG[29]) to conduct a series of field tests of the open-water mechanical recovery system designed to collect data on recovery efficacy. The project should include modeling of wind and sea state effects for conditions that exceed the safety limits set for the field tests.

2. **ADD VISIBILITY MEASUREMENTS TO THE ANALYSIS**

   Fitting the NOAA data buoys with visibility instrumentation or agreeing to a method to capture reliable mariner observations as a valid measure of visibility could also improve the accuracy of the Response Gap measurements. We recommend the RCAC explore these options with NOAA.

3. **CONDUCT SENSITIVITY ANALYSIS AND CALCULATE DURATION STATISTICS ON THESE DATA**

   Additional analyses of the data gathered for this report might also clarify the Response Gap. A sensitivity analysis would shed light on the effect each variable has on the Response Gap measurement and how changing the response limits and/or closure limits would affect the Response Gap estimate. An analysis of the frequency and duration of series in the dataset where the RGI is deemed red would indicate the probability of mounting a spill response for any given time period. We recommend the RCAC further explore these data.

4. **EXPLORE WAYS TO LOWER THE RESPONSE GAP BY INCREASING RESPONSE CAPABILITY**

   The RCAC should immediately work with SERVS and the RPG to initiate a project to increase the ability to find, track, and recover oil in hours of darkness. After the research on response limitations from Recommendation #1 is completed, the RCAC should work with SERVS and the RPG to identify existing equipment or technologies that would bolster the weakest links in the response system. If such technologies do not exist, then PWSRCAC should work with SERVS and the RPG to develop new technologies to increase response capabilities.

29 The Response Planning Group (RPG) consists of the PWS Tanker C-plan planholders.

5. CONDUCT A RESPONSE GAP ANALYSIS IN OTHER OPERATING AREAS

A Response Gap analysis should be conducted for the Valdez Arm operating area because this region is subject to high winds and low visibility and is know to have very different conditions than those of either Central PWS or Hinchinbrook Entrance. However, better environmental observations are needed for this analysis to be conducted. Wind and air temperature observations are available at the Bligh Reef Coastal-Marine Automated Network (C-MAN) station operated by the NDBC, but sea state and visibility data are not available. It would be possible to predict sea state from winds using a wave model, but this would introduce a source of error into the analysis. A source of visibility observations would also be required.

6. QUANTIFY RESPONSE LIMITATIONS AND CONDUCT A RESPONSE GAP ANALYSIS FOR NEARSHORE RESPONSE SYSTEM

A Response Gap analysis should also be conducted for the nearshore response system, but first a response limitation for this system should be quantified using the methods in Recommendation #1.

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Appendix A: Terminology

Response Gap RCAC's request for proposals for this project states, *"The Response Gap is the window between the point of maximum capability to mechanically respond to an oil spill in a safe manner, and the point where the conditions reach Closure Limits (15 foot seas or 45 knot winds) at which point Hinchinbrook Entrance is closed to outbound laden tankers."*[30]

Closure Limit The Prince William Sound Vessel Escort Response Plan (VERP) is the port-specific operations plan adopted by the Prince William Sound Owners/Operators. The VERP states, "outbound laden tankers will not be allowed to transit Hinchinbrook Entrance when winds exceed 45 knots or seas exceed 15 feet." It further states that these conditions will be determined based on the weather buoy at Seal Rocks.[31] Thus, the Closure Limit is the upper limit of environmental conditions where oil is transported through Prince William Sound.

Environmental Factor An environmental factor is an aspect of meteorological or oceanographic conditions that can impede or prevent response operations. Environmental factors include: wind, waves, visibility, temperature, currents, and ice.

Nearshore Oil Spill Recovery System The PWS Tanker Plan describes two types of response systems for the mechanical recovery of oil on water: open-water response and nearshore response. Nearshore response is considered the second tier of response operations after open-water response. Nearshore response consists of free-oil recovery and shoreline protection, and is based mostly on small vessels of opportunity (primarily fishing vessels). The operational limits of the Nearshore Oil Spill Recovery System are less than that of the Open-water Oil Spill Recovery System. Since the open-water oil spill recovery system is the primary response system intended to meet the Response Planning Standard, the nearshore response system is not being considered as part of this analysis.

Observation An observation is a single measurement of an Environmental Factor, such as wind speed or wave height.

Observational Period An observational period is the time covered by an observation. For the purposes of this analysis, an observational period will be one hour. Note, however, that wind speed observations reported are 8-minute-average wind speeds, that is, wind speeds recorded and averaged over an 8-minute period each hour. These wind speeds represent sustained wind speeds and are the data used by the USCG's Marine Safety Division, Valdez in determining whether closure conditions are satisfied at Hinchinbrook Entrance.

Open-water Oil Spill Recovery System The PWS Tanker Plan describes two types of response systems for the mechanical recovery of oil on water: open-

30 RCAC RFP 756-06-01
31 National Data Buoy Center buoy 46061.

water response and nearshore response. Open-water response is considered the first tier of response operations; nearshore response is the second. Open-water response consists of containment and removal of oil floating on the water, and is based mostly on large, dedicated response vessels. Some vessels of opportunity (primarily fishing vessels) are used in open-water response to tow oil containment boom. The operational limits of the open-water oil spill recovery system are greater than that of the nearshore oil spill recovery system. *This study focuses on the open-water oil spill recovery system as the primary response system intended to meet the Response Planning Standard.*

Operating Area An operating area is a geographic zone where oil spill response operations might occur. Since the PWS region is large and diverse, it is being subdivided into operating areas where similar environmental conditions are expected to occur. For instance, environmental factors in Valdez Arm can be very different from Central Prince William Sound at any given time. The term *operating area* is analogous to the response "zones" used in the PWS Tanker C-plan.

Operating Environment The operating environment is the anticipated environmental context where an oil spill response might occur. Examples include: open-water, protected-water, and calm-water. There are at least two different classification schemes for operating environments. For this study, we are using the scheme established by the American Society for Testing and Materials (ASTM).

Realistic Maximum Response Operating Limitation (RMROL) This term is defined in the Alaska Department of Environmental Conservation's (ADEC) Oil and Hazardous Substance Pollution Control Regulations as "the upper limit of a combination of environmental factors that might occur at a facility or operation beyond which an operator would be unable to mount a mechanical response to a discharge event."[32]

Response Planning Standard (RPS) Response Planning Standard (RPS) is defined in the ADEC regulations as a planning standard against which the adequacy of an oil discharge prevention and contingency plan will be judged by ADEC. It does not constitute a cleanup standard that must be met by the holder of a contingency plan.[33]

Response Gap Index (RGI) The Response Gap Index is a derived barometer/index used in this study to combine multiple environmental factor observations into a single indication that the maximum operational limit has been exceeded for the observational period.

32 Alaska Regulations 18 AAC 75.990(56).
33 Alaska Regulations 18 AAC 75.990(57).

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