Estimating Design Temperatures in Arctic Environments: A New Approach

by Heri Sulistiyono

Estimating Design Temperatures in Arctic Environments: A New Approach

Heri Sulistiyono
Faculty of Engineering
University of Mataram
Lombok, Indonesia

Leonard M. Lye, Faisal I. Khan, Ming Yang
Faculty of Engineering and Applied Science
Memorial University of Newfoundland
St. John's, NL, Canada, A1B 3X5

Dan Oldford, John Dolny
Harsh Environment Technology Center
American Bureau of Shipping (ABS)
St. John's, NL, Canada, A1B 3X5

Abstract*— Over the past eight decades the ice-infested Northern Sea Route (NSR) has been steadily developed although historically it has been of little interest to commercial shipping companies. However, the shorter routes, more open waters, and the increasing demand for shipping have caused shipping companies to reconsider shipping along these routes. The NSR is now part of an overall world transportation system. However, a key problem of shipping in Arctic environments is the extreme low temperatures encountered and sea ice during most of the year. The American Bureau of Shipping (ABS) has provided some guidance for shipping along the Arctic sea routes with winterization of the Arctic going vessel as a suggested requirement. The technology and level of winterization is determined by the design service temperature (DST) estimated by the lowest mean daily average temperature (MDAT) over at least a 20-year period for the intended geographical area and season of operation. Systems that are more susceptible to the lower temperatures have another temperature which ABS designates as the Minimum Anticipated Temperature (MAT). However, the suitability of that value with respect to a risk based assessment on a vessel and its systems is questionable. For a modern risk-based approach to winterization, knowledge of the magnitude and frequency of occurrence for a given duration are prerequisites. This paper presents a new and more rational approach to estimate the DST or MAT. The approach is based on the set of Temperature-Duration-Frequency (TDF) curves developed for a given climate station. For this study, the Arctic was divided into four regions. Annual extreme low temperatures of durations 1, 3, 6, 12, 24, 36, 48, 72, 96, 120, 144, and 168 hours were extracted from the last 20 years of historical record from three to four representative stations in each region. Magnitudes of low temperatures were then estimated from the data for return periods ranging from 2 to 100 years. These estimates are then used to construct the TDF curves that provide estimates of the magnitude of extreme low temperatures for a given return period, for various durations of practical interest. It is proposed that the 100-year return period 1-hour duration lowest extreme temperature be used as the estimate of the MAT. The proposed approach addresses the drawbacks of the current approach and provides a practical estimate of the DST or MAT for risk-based winterization decisions.

Keywords—design service temperature, temperature-duration-frequency curves, annual extreme low temperatures, Arctic environments, and winterization.

I. INTRODUCTION

The Northern Sea Route (NSR) was previously of little interest to commercial shipping companies. However, over the past eight decades the ice-infested sea route has been steadily developed [1], [2]. This is because taking the NSR may reduce the number of days at sea and increase the overall fuel efficiency of transporting cargo [3]. Another reason to consider the NSR is due the gradual shrinkage of the Arctic caps due to climate change creating more open waters. The increasing demand for shipping has also caused shipping companies to reconsider traffic along the NSR. Hence, shipping traffic along the NSR is expected to increase considerably in future due to increases in the size and frequency of ships traveling along the route [4]. The route passes through the Arctic seas including: the Barents Sea, the Kara Sea, the Laptev Sea, the East Siberian Sea, the Chukchee Sea, and partially through the Bering Sea. The NSR is now part of an overall world transportation system.

The Arctic-shipping route cuts thousands of kilometers off shipping and reduces many days off the journey from Asia to its key European market. Savadove [5] has reported that a vessel owned by Chinese state shipping giant "COSCO" travelled from the northeastern port of Dalian to Rotterdam in the Netherlands, a 5,400-kilometre (3,380-mile) voyage, took only about 30 days. This is a saving of 12 to 15 days from the traditional route through the Suez Canal. Fig. 1 shows the difference in distance between the NSR and the traditional Suez Canal route.

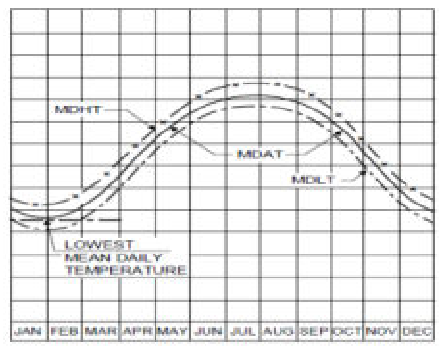
The NSR is currently only open for about four months a year due to ice conditions and the lack of other service infrastructure. But as the polar ice melts as a result of climate change the waters will be more accessible in future. A paper published in Arctic, a journal of the University of Calgary's Arctic Institute of North America, reports that between 1961 and 1985, the ice cap grew in some years and shrank in others, resulting in an overall loss of mass. But that changed in 1985 when scientists began to see a steady decline in ice volume and area each year [6]. The extreme ice melting in the Arctic sea of 4.28 million km^2 in 2007 has reignited interest in efforts to constitute new trade passages, fostering the possibility of economically feasible trans-Arctic shipping as well as greater access to regional resources and spurring development in localized shipping, natural resource extraction, and cruising as part of tourism [7].

Fig. 1: Northern Sea Route (NSR) versus the Suez Canal route, [8].

II. DESIGN TEMPERATURES

Problems of shipping along the Arctic Sea Routes: the NSR and the NWP are largely due to the harsh climate of the Arctic [9]. Therefore, understanding the behavior of extreme low temperatures in the Arctic region is a prerequisite. The American Bureau of Shipping (ABS) has provided guidance for shipping along the Arctic Sea Routes [10]. Winterization is a suggested requirement in the guidance. The design service temperature (DST) and the Minimum Anticipated Temperature (MAT) are a couple of important factors to determine the technology and level of winterization. In [11] DST is defined as the lowest mean daily average temperature in the area of operation for data taken over at least a 20-year period. Not only for determining the technology and level of winterization, vessels operating in low temperature environments have to be certified regarding their hull structural materials which have to be designed based on the DST and appropriate material class in accordance with the ABS *Steel Vessel Rules*, (6-1-2/23 for Polar Classes, 6-1-5/33 for First Year Ice) and IACS UR S6.2 or the ABS Guide for Vessels Operating in Low Temperature Environments Section 2 for non-ice classed vessels. For example, materials used for essential equipment exposed to the weather must be of steel or other suitable material with ductility properties at the minimum anticipated temperature for which the equipment is to operate. This is can be defined as 20°C below the DST.

The DST is obtained by using the Lowest Mean Daily Average Temperature (LMDAT) as illustrated in Fig. 2 and 3. The MDHT and MDLT stand for Mean Daily High Temperature and Mean Daily Low Temperature, respectively [10], [12]. This current practice only provides the magnitude of the DST. It does not provide information about the duration and the frequency of occurrence or probability of exceedance of the estimated DST. The suitability of this approach with respect to a risk-based assessment on a vessel and its systems is questionable. For a modern risk-based approach to winterization, knowledge of the magnitude and frequency of occurrence for a given duration are prerequisites.



MDHT: Mean Daily High Temperature
MDAT: Mean Daily Average Temperature
MDLT: Mean Daily Low Temperature
LMDT: Lowest Mean Daily Temperature - (Design Service Temperature)

Fig. 2: Plot of Design Service Temperature [10].

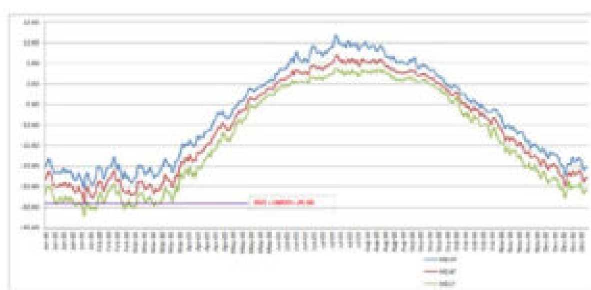


Fig. 3: Plot of Design Service Temperature for the Barrow Station, Alaska.

The LMDAT is based on average or mean values and not on extreme values. Therefore, the use of a lowest mean daily average temperature (LMDAT) as the only design temperature would provide severe underestimation of the annual extreme low temperatures of various durations. The MAT as defined by DST -20°C may overestimate the extreme lows.

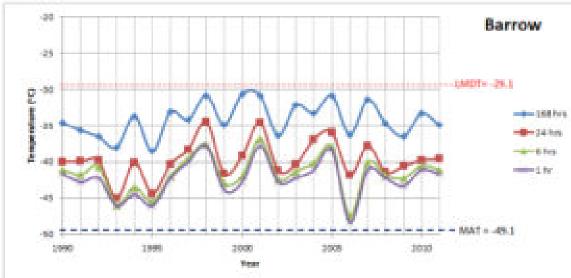


Fig. 4: Comparison of Extreme Low Temperatures to LMDT for the Barrow Station.

Figure 4 illustrates this point using the Barrow temperature data. As shown in Fig. 4, extreme low temperatures at various durations occur below the LMDT but typically well above the MAT. This means that the current practice of using the LMDAT and LMDAT -20°C would likely over or underestimate the adequate winterization levels. Therefore, this paper presents frequency analysis of extreme low temperatures and proposes Temperature-Duration Frequency (TDF) for determining the MAT that provides information including the duration and the probability of exceedance of various durations in four regions of the Arctic.

III. PROPOSED METHODOLOGY AND RESULTS

This study proposes the development of Temperature-Duration-Frequency (TDF) graphical method to improve the performance of the current practice for determining a MAT. The proposed methodology involves selection of weather stations in the Arctic regions, selection of climatic variable, observation of extreme low temperatures, identification of extreme low temperature distribution at various durations, the development of TDF based on probability of exceedance.

A. Selection of Weather Stations in the Northern Hemisphere (Arctic Regions)

In this study, the Arctic was divided into the following four regions: Region 1 spans from 180 ° to 90 ° West Longitude or Alaska to Canada, Region 2 spans from 90 ° West to 0 ° Longitude or Greenland to the United of Kingdom, Region 3 spans from 0 ° to 90 ° East Longitude or along the Scandinavian coast, and Region 4 spans from to 90 ° East to 180 ° Longitude or along the northern Russia's coast. These four regions are shown in Fig. 5.

The purpose of dividing the Arctic areas into four regions is to ease the analysis of extreme low temperature characteristics based on the assumption that the four regions have different characteristics of extreme low temperatures. Each region is represented by 4 weather stations giving a total of 16 stations. The selection of weather station was based on several parameters include the length of available data, elevation, spread, and closeness to the sea.

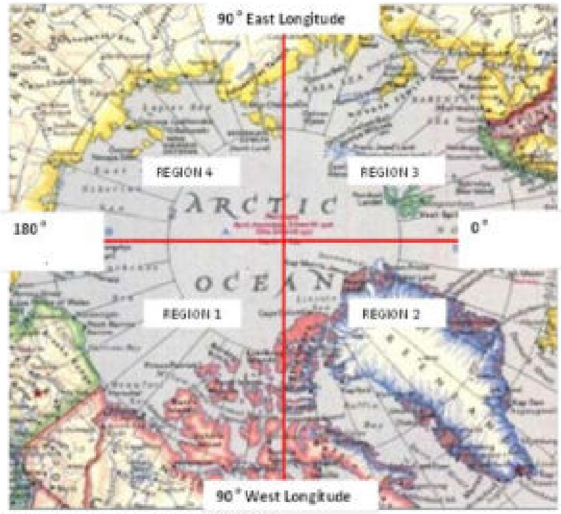


Fig. 5: Division of the Arctic Region

B. Selection of Climatic Variable

Hourly recorded temperature data were chosen as the climatic variable to be analyzed. This proposed procedure suggests that at least 20 years of hourly data should be adequate, although longer periods of data are more preferable. The data were obtained from the website of the National Climatic Data Center provided by the National Oceanic and Atmospheric Administration (NOAA).

In this proposed approach, hourly temperature data were analyzed based on various durations: 1, 2, 3, 4, 6, 8, 12, 24, 32, 36, 40, 48, 56, 72, 96, 120, 144, and 168 consecutive hours. The method of moving average was applied in this analysis to obtain the minimum values of durations. The minimum values were then noted for all available years. These minimum values were then called the annual extreme low temperatures for the given duration. As data used in this study ranged 20 years, therefore 20 data points of annual and monthly extreme low temperatures are determined in this process and ready for the use for further analysis.

C. Identification of Extreme Low Temperature Distributions at Various Durations

Distribution of annual extreme low temperature data is important for obtaining probability of exceedance of the extreme low temperature. Several types of statistical distribution were investigated to obtain the best match of annual low temperature distribution including normal, log normal, gamma, Weibull, exponential, extreme values, and logistic. A significance level of 5 % was used to judge whether a distribution is acceptable. The method of Maximum Likelihood was used to obtain the distribution parameters. Kolmogorov-Smirnov (K-S) test was used as the goodness of fit test in this study. According to Wilcox [13], extant studies comparing the power of the Kolmogorov-Smirnov test to other methods for comparing means shows the Kolmogorov-Smirnov test not only can have high power relative to other methods for comparing robust measures of location, there are situations where it has higher power than methods for comparing robust measurement of location. The Kolmogorov-Smirnov test was programed using an excel spreadsheet in this study. The use of excel rather than the use of commercial statistical software is to ease any individual practice to conduct goodness of fit test without worrying about having licensed commercial software.

Our analysis shows that the normal distribution cannot be rejected at the 5% level for all durations. This was also confirmed by the Anderson-Darling test.

D. Temperature-Duration-Frequency (TDF) Graph

The probabilities of exceedances of extreme low temperatures are determined using the fitted probability distribution. Probabilities of selected annual extreme low temperature of various durations at the Barrow station are presented in Table I.

TABLE I. Probabilities of annual extreme low temperatures of various durations at the Barrow Station.

Prob	1	12	24	36	48	72	168
0.5	-42.3	-41.0	-39.8	-38.7	-38.0	-36.9	-34.0
0.2	-44.6	-43.3	-42.1	-41.0	-40.3	-39.2	-36.1
0.1	-45.8	-44.4	-43.3	-42.2	-41.6	-40.3	-37.1
0.05	-46.8	-45.4	-44.3	-43.2	-42.6	-41.3	-38.0
0.02	-47.9	-46.5	-45.5	-44.4	-43.7	-42.4	-39.0
0.01	-48.6	-47.2	-46.2	-45.1	-44.5	-43.1	-39.7

Table 1 shows that at Barrow, an average extreme low temperature of -42.3 °C over a duration of 1-hour occurs every two years on average; and, an average extreme low temperature of -48.6°C over a duration of 1-hour occurs every 100 years on average. The average extreme low temperature rises as the duration increases. Table 1 also shows that the difference between the hourly (1-hour) extreme low temperature and the daily (24-hour) extreme low temperature is about 2~3°C and the difference between the daily extreme low temperature and the weekly (168 hour) extreme low temperature is about 5~7°C, among those probabilities of exceedances. This suggests that extreme low temperatures at this station do not vary by much from year to year and from hour to hour. Subsequently, the frequency analysis at each duration can be combined and summarized into a temperature-duration-frequency (TDF) plot as shown in Fig. 6 for the Barrow Station.

A DST determined from Figure 6 provides information on the probability of exceedance and duration. For example, for a 24-hour duration, if - 46 °C is chosen as the MAT for Barrow, the probability of exceedance is about 1%. This means that the probability of the average 24-hour temperature at Barrow of – 46 °C or below is very low. It only occurs on average once in every 100 years.

Analog to the annual extreme low temperature analysis, the monthly analysis can be conducted to obtain the probabilities of extreme low temperature of various durations in every month. Both annual and monthly extreme low temperature analyses are important to determine the annual and monthly MAT. An annual MAT is important for vessel and other activities that continually operate for a long time in the regions. A monthly MAT is important for vessels and other activities that periodically operate for a certain time in the regions. The authorities of Arctic operations can choose the best month to operate their vessels and other activities and decide additional plans, such as the technology of winterization to support their operations. Results of TDF curves of 4 stations from 4 regions and the results of TDF curves of 16 stations can be provided from the authors.

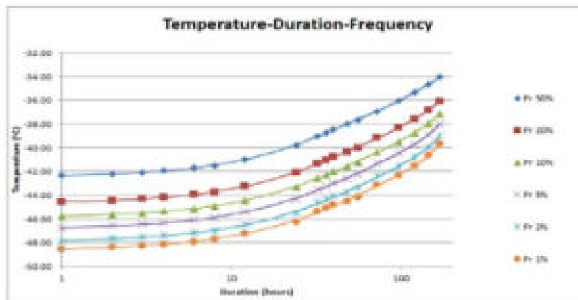


Fig. 6: Temperature-Duration-Frequency (TDF) plot of annual Low Temperatures at the Barrow Station.

IV. CONCLUSIONS

MAT is important for the development of ship winterization technologies and for selecting the winterization level of ship operating in harsh environments. The IACS UR S6 method for estimating DST has been acceptable in industries for some material applications. However up to now, limited guidance is offered in the selection of MAT other than DST -20°C, especially with regard to probability and risk. As a modern risk-based approach to winterization requires knowledge of the magnitude and probability of occurrence, a new approach of MAT estimation method based on the set of Temperature-Duration-Frequency (TDF) curves has been successfully developed in this study. The proposed method provides more comprehensive information of DST.

This study has developed TDF curves of several representative climatology stations to study the statistical characteristics of extreme low temperatures in the Arctic region. The Arctic region has been divided into four regions: Region 1 (Alaska ~ Canada), Region 2 (Greenland ~ the United of Kingdom), Region 3 (along the Scandinavian coast), and Region 4 (along the northern Russia's coast). This study has developed all calculation procedures in a template of excel spreadsheet to avoid licence problems of commercial software for any individual interest.

ACKNOWLEDGMENT

The authors acknowledge the financial support for this research from the American Bureau of Shipping (ABS) through the Harsh Environment Research Program.

Disclaimer

The views expressed herein are those of the authors and are not to be construed as official views of ABS.

REFERENCES

[1] J. Drent, Commerical shipping on the northern sea route. The Northern Mariner, III, No. 2, http://cnrs-scrn.org/northern_mariner/vol03/tnm_3_21-17.pdf, 1993.

[2] PAME, The Arctic marine shipping assessment: history of Arctic marine transport, 2009.

[3] C. L. Ragner, Northern Sea Route cargo flows and infrastructure present state and future potential. FNI Report. Fridtjof Nansen Institute, Postbooks 326, N-1326 Lysaker, Norway, 2000.

[4] M. Humpert, The future of the Northern Sea Route – A "Golden Waterway" or a niche trade route. The Arctic Institute/Center for Circumpolar Security Studies, 2011.

[5] B. Savadove, China begins using Arctic shipping route that could 'change the face of world trade', Business Insider, 2013.

[6] R. Klinkhammer, Decades of research show massive Arctic ice cap is shrinking. Arctic, University of Calgary's Arctic Institute of North America, 2010.

[7] S. Dasgupta, How the ice melting in the Arctic has affected the shipping industry. Marine Insight, 2011.

[8] Northern Sea Route Information Office, China's new shipping frontier, 2013.

[9] O. Luskutova, The Northern Sea Route expects active maritime traffic, Maritime Market E-magazine, 2006.

[10] ABS, Guide for vessel operating in low temperature environments. Houston, USA, 2010.

[11] E. Legland, R. Conachev, G. Wang, and C. Baker, Winterization guidelines for LNG/CNG carriers in Arctic environments. ABS Technical papers, 2006.

[12] M. Yang, F. Khan, L. M. Lye, H. Sulistiyono, J. Dolny,and D. Oldford, Risk-based winterization for vessels operations in Arctic Environments, Journal of Ship Production and Design, 29(4), 199-210, 2013.

[13] R. R. Wilcox, Some practical reasons for reconsidering the Kolmogorov-Smirnov test. British Journal of Mathematical and Statistical Psychology. DOI: 10.1111/j.2044-8317.1997.tb01098.x, 2011.

Estimating Design Temperatures in Arctic Environments: A New Approach

ORIGINALITY REPORT

5%	5%	0%	0%
SIMILARITY INDEX	INTERNET SOURCES	PUBLICATIONS	STUDENT PAPERS

MATCH ALL SOURCES (ONLY SELECTED SOURCE PRINTED)

3%

★ www.semanticscholar.org

Internet Source

Exclude quotes	On	Exclude matches	< 3%
Exclude bibliography	On		

Estimating Design Temperatures in Arctic Environments: A New Approach

GRADEMARK REPORT

FINAL GRADE

/0

GENERAL COMMENTS

Instructor

PAGE 1

PAGE 2

PAGE 3

PAGE 4

PAGE 5