

Arctic Space Weather Enhancing Aurora Watch Planning of Arctic Cruises During Polar Tourism Peak Seasons

Summer 2025 | Virginia – Langley
August 8th, 2025

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Abstract:

This study, in partnership with The Polar Adventure Company (TPAC), investigated the use of Earth observations to detect auroral phenomena and forecast future auroral trends at cruise ports in Alaska, United States. TPAC currently relies on experiential knowledge for cruise planning around aurora viewing. An analysis of historical solar cycle (SC) data, to estimate upcoming SC activity impacting auroral occurrence and intensity, may provide basis for more comprehensive cruise planning. This study employed remote sensing data from the Suomi-NPP VIIRS Day-Night Band (DNB) to validate the OVATION Prime (OP) model, a space weather prediction tool which outputs energy flux of precipitating particles in aurora regions. Sunspot number correlations between current SC data and prior SC data ensured higher accuracy in forecasting. Cycle comparison yielded a 30% strength increase from the previous SC to current. Planetary (Kp) and Auroral Electrojet (AE) indices trends of historical auroral activity in relation to OP data were used for forecasting. OP has a minimal detectable energy flux, or critical value for optical detection of aurora by human's naked eyes. Relationships between OP and the Kp index as functions of latitude yielded Kp critical values for three latitude ranges in the Alaskan region. Aurora occurrence probabilities by month in upcoming years were generated by examining how often the critical value was exceeded for each region in historical geomagnetic data. The end products include a probability map showing the potential visibility of aurora at each Alaskan port for an expedition voyage in 2026.

Key Terms: VIIRS, Earth observation, Aurora Borealis, space weather, OVATION Prime

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1. Introduction

Auroras have captivated humans as far back as the 10th century, with a recent study predating Assyrian auroral reports by three centuries (van der Sluis & Hayakawa 2023). The Aurora Borealis is an observable phenomenon resulting from interactions between solar electromagnetic radiation and the Earth's magnetic field. The Sun emits solar wind, a supersonic plasma flow that travels through the heliosphere, reaching planetary bodies, including Earth. Earth's magnetic field funnels particles from the solar wind toward Earth's geomagnetic poles, around which they enter the upper atmosphere. As particles collide with atmospheric molecules, visible light is emitted as purple, green, and red aurora (Seaman & Miller, 2013). There are two main solar processes through which auroras may be intensified: solar flares and coronal mass ejections (CME). Both are the result of explosive releases of magnetic energy stored in the outermost layer of the Sun, the corona (Gosling, 1993; Khazanov et al., 2019). Sunspot numbers have been recorded since 1749 and fluctuate with the 11-year solar cycle (SC). Higher sunspot numbers correlate to the maximum in the SC, including more frequent solar flares, CMEs and geomagnetic storms (Sunspots, n.d.), which may affect aurora presence and intensity.

The acquisition of space weather data with optical imagery has numerous limitations, for example, variables such as cloud cover obstructing optical imaging, causing variations in the daily availability of data. Thus, the current state of auroral forecasting is limited to short term predictions on the scale of minutes to days. Remote sensing methods from spaceborne satellites have been employed to provide global spatiotemporal data for historic analysis and possible assistance in prediction. The Suomi National Polar-orbiting Partnership (Suomi-NPP) satellite equipped with the Visible Infrared Imaging Radiometer Suite (VIIRS) enables the effective visualization of auroral lights through the Day/Night Band (DNB; Miller et al., 2013). Launched in late August of 1997 (NASA, 2024), NASA's Advanced Composition Explorer (ACE) spacecraft was designed to provide upstream information on interplanetary magnetic field and solar wind at the Sun-Earth Lagrange point (L1). ACE data functions as an input of solar wind measurements for the OVATION prime (OP) model. The OP 2.3 version models auroral precipitation with the parametrization of solar wind driving (Machol et al., 2012; Newell et al., 2014).

In addition to remote sensing data, auroral activity is monitored with indices, such as the Auroral Electrojet index (AE) and Planetary K-index (Kp). The AE is a gauge of solar wind intensity at high latitudes (Khazanov, 2019). The AE is derived from the Auroral Electrojet Upper (AU) and Auroral Electrojet Lower (AL) indices. The AU and AL represent the strongest current intensities of the eastward and westward auroral electrojets respectively, as measured by a network of high latitude magnetometers (Luo et al., 2013). Magnetic variations in the Earth's field obtained at 13 globally distributed subauroral magnetometer stations provide data for the Kp index (Matzka et al., 2021; Thomsen, M.F., 2004).

The integration of various auroral data sources, such as remote sensing data, prediction models, and indices, may address some of the limitations related to data availability when attempting long-term forecasts. The goal of this feasibility study was to attempt this integration for the project partner, The Polar Adventure Company (TPAC), which specializes in experiential tourism in the Arctic region. The partner seeks a probability map for customers to inform their choice of tour based on the likelihood of viewing Auroras on various upcoming voyages from 2026 to 2028. Currently TPAC relies solely on their intuition from personal experiences to guide customers in aurora-chasing; itineraries are planned around wildlife viewing, historical settlement locations, geology, and arctic scenery, TPAC hopes to add scientifically-backed aurora watching to their itineraries.

The team narrowed the focus of auroral activity analysis to Arctic Alaska (Figure 1), the region of best aurora visibility within the United States. While aurora occurs throughout the year, the lights are only visible during nocturnal periods. Due to Earth's axial tilt, there are prolonged periods of continuous daylight during the summer season, so the team refined the study period to the months of mid-August through October 2026-2028. This aligns with the greatest periods of darkness in the Arctic Circle and coincides with the latter end of the Arctic peak tourism season.

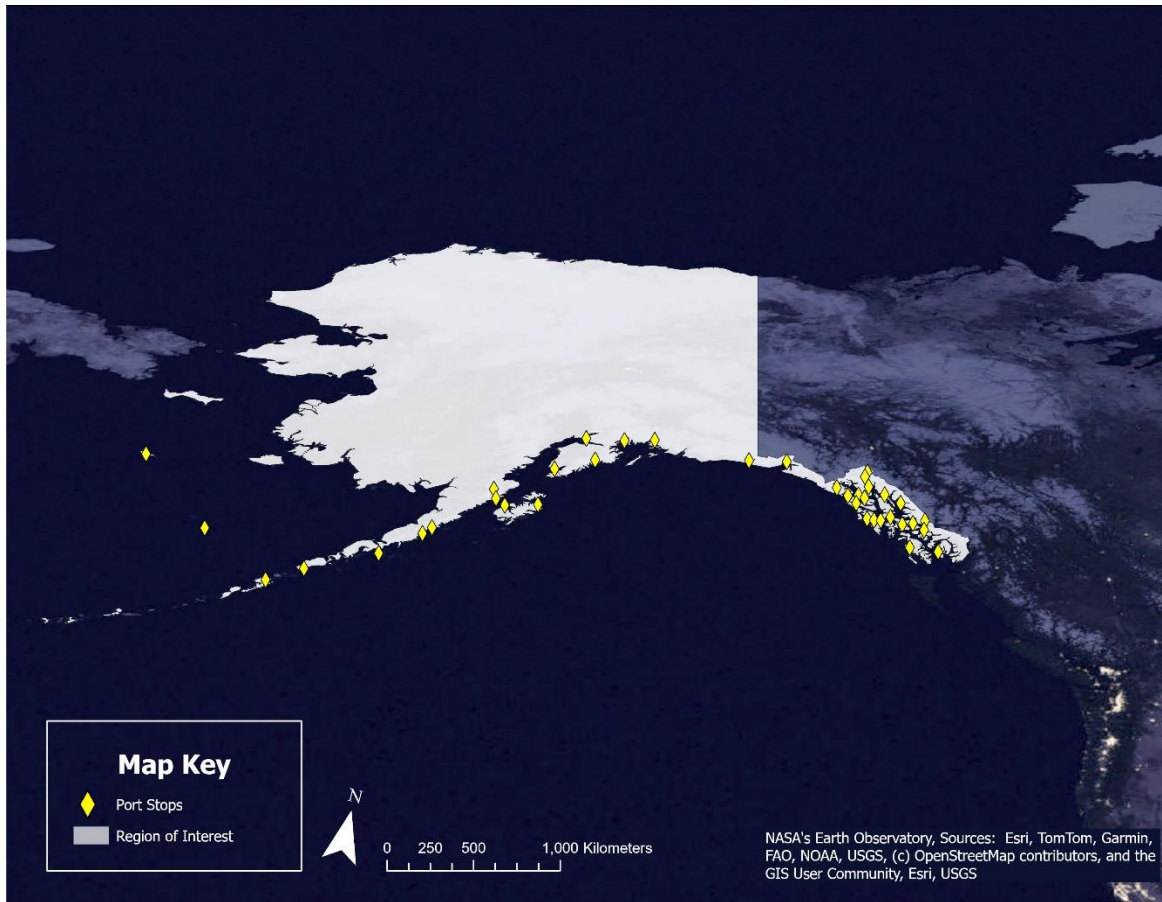


Figure 1. Alaskan port stops along The Polar Adventure Company voyages from 2025 to 2028.

2. Methodology

2.1 Data Acquisition

2.1.1 Observational Data

The team acquired imagery from the Suomi-NPP VIIRS DNB (Table 1) sensor through NASA Worldview's Level 1 Atmosphere Archive & Distribution System Distributed Active Archives Center (LAADS DAAC) for the selected case study date of September 20th, 2023. The team selected this case study based on validated auroral substorm event indicators from both the Kp and AE indices. Additionally, we acquired data from Aurorasaurus (Table 1), a citizen science platform that allows for users to report whether or not auroras were visible in their area at any given time on any given night. The Aurorasaurus team provided files in the format of comma separated value (CSV), which included: longitude, latitude, and positive or negative sighting indication. This approach enabled the team to identify auroral trends utilizing remote sensing techniques complemented by ground-based validation efforts.

Table 1

Observational data.

Data Name	Data Source	Type/Level	Requests
VIIRS VPN46A1 (5200) Day/Night Band	NASA LAADS DAAC	Low Light Optical Imagery (Level 1)	9/15/2023, 9/20/2023

Aurorasaurus	Elizabeth MacDonald, Aurorasaurus Founder	Citizen Science Aurora Reports	9/20/2023, 08/14 - 10/31 2014 - 2017
OVATION Prime	CCMC	Historical solar wind intensity	9/20/2023, 08/14 - 10/31 2014 - 2017
Kp	WDC for Geomagnetism, Kyoto	Auroral Index	9/20/2023, 08/14 - 10/31 2014 - 2017
Sunspot Number	NOAA SWPC	Historical Catalog	12/2008 - 12/2030
AE	WDC for Geomagnetism, Kyoto	Auroral Index	9/20/2023, 08/14 - 10/31 2014 - 2017

2.1.2 Geomagnetic and Solar Measurements

The team collected geomagnetic index data recorded during the SC 24 (2008-2019) declining phase (2014-2017). These data are useful as a historical trending basis in forecasting the activity over the decline phase of cycle 25 (2025-2030). The team collected Op data (Table 1) from the Community Coordinated Modeling Center (CCMC) containing one-minute OMNI solar wind measurements, and solar wind ion and electron precipitation fluxes every five minutes. Kp and AE data (Table 1) were obtained from the World Data Center (WDC) for Geomagnetism, Kyoto. Kp indices are provided every three hours with the variation in global geomagnetic activity. AE measures the auroral electrojet currents at high latitudes which are provided on an hourly temporal scale.

Additionally, the team sourced sunspot number (SSN) data (Table 1) from NOAA's Space Weather Prediction Center (SWPC) counting the number of visible spots on the Sun's surface. SWPC provides this information through their website in JavaScript Object Notation (JSON) files, including information for the date, sunspot number, and solar radio flux at a wavelength of 10.7cm (F10.7). This information dates to 1749 on a monthly scale and 1996 on a daily scale. Furthermore, predicted SSN is accessible containing data up to 2030 with low, 25th, 75th, and high percentile predicted ranges for SSN and F10.7 on a monthly scale.

2.1.3: OP Prediction Model

CCMC computed OP text (txt) formatted data for the previous SC study period: August through October, 2014-2017. The team selected one-minute omni solar wind input data to inform the CCMC model of the environment. Additionally, they utilized observed auroral precipitation from the archive setting and set the temporal model output to a five-minute (300s) interval.

2.1.4: TPAC Cruise Information

TPAC provided data of global cruise itineraries and port stop locations for the years 2025 through 2028 in comma separated value (CSV) files. They provided insight into times of year for peak tourism and aurora viewing conditions for passengers while on board and at port stops along with imagery of cruise ships and aurora. Data and insight from TPAC informed study area selection, study period selection, and helped to identify limitations of this study.

2.2 Data Processing

2.2.1 Observational Data

For VIIRS DNB data, the team removed anthropogenic light pollution from satellite imagery utilizing ArcGIS Pro version 3.5.0. We applied a masking technique using data from a non-auroral substorm day (September 15, 2023) to identify light pollution without aurora presence. The GIS remap function allocated the light pollution pixels to "no data" values, and applying this filter to the case study data (September 20, 2023) removed light pollution pixels. The resulting dataset exclusively held auroral data to bolster the accuracy of analysis and visualization (Figure 2).

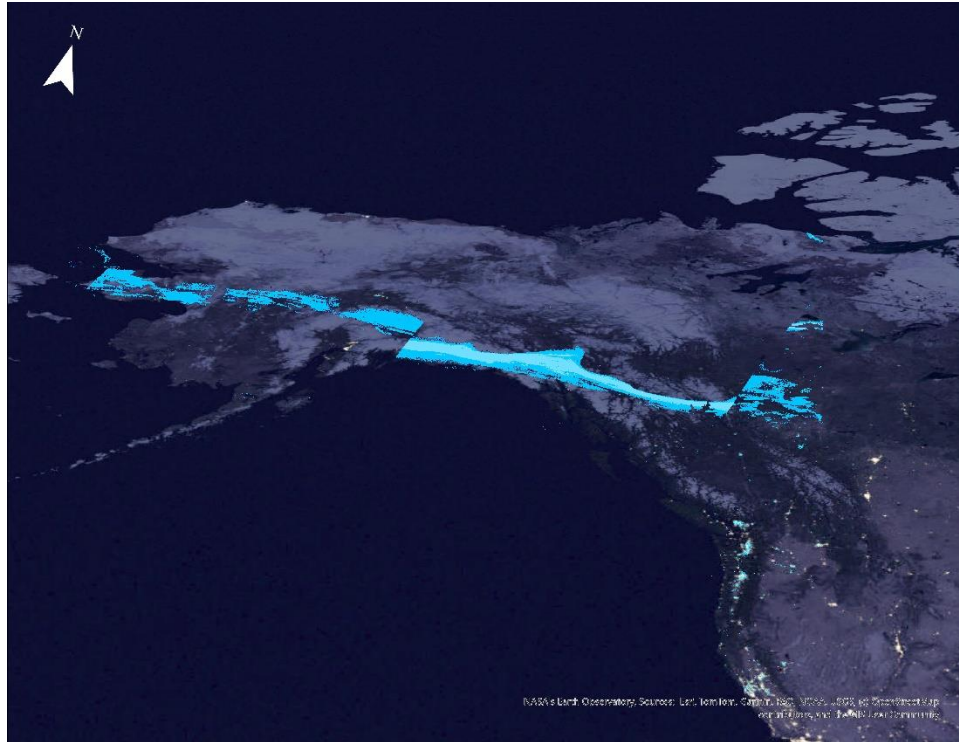


Figure 2. September 22nd, 2023, VIIRS imagery capturing Aurora Borealis

The Aurorasaurus team provided Python code, version 3.11.13, for altitude-adjusted corrected geomagnetic (AACGM) coordinate conversion of the geographic coordinates provided in user reports. The code also allowed for the removal of duplicate entries and entries with durations longer than twelve hours. The team created original code in Python version 3.11.13 to remove entries outside of Arctic Alaska and chose study periods. Aurorasaurus data were processed for the purpose of validation for visible aurora on the chosen case study date, September 20th, 2023, during data analysis. However, after processing, we found that there were no reports in the Alaska region on the chosen case study date. Thus, Aurorasaurus did not carry on into data analysis and validation occurred using only VIIRS for this case study.

2.2.2 Geomagnetic and Solar Measurements

The team wrote original Python code, version 3.11.13, to process index and SSN values. Kp data are recorded at three-hour temporal intervals. Kp data were integrated with OP and AE data--normalized to match the Kp temporal resolution. AE minimum, maximum, median, and mean values were calculated for each three-hour Kp interval. KP, AE, and OP data were combined into the same CSV file. The team filtered and separated the monthly recorded sunspot numbers into SCs 24 and 25 with the predicted values added to SC 25 data.

2.2.3 OP Prediction Model

The team developed original Python code, version 3.11.13 to automate data extraction from the model output, selecting files that contained energy flux values for both electrons and ions. Further processing converted the raw model outputs into analysis-ready data by reformatting from txt to CSV files with refined datetime. The AACGM-v2 (version 2) package facilitated coordinate transformations between the OP output information--in AACGM coordinates--to geographic coordinates. Subsequently, the team refined the data to within the study area, calculated three-hour statistics for particle flux and AE.

2.2.4 TPAC Cruise Information

The team reorganized the data provided by TPAC, with original Python code, version 3.11.13, filtering the list of port stops to those within Arctic Alaska. We created a new CSV file with port names, geographic

coordinates, and equivalent geomagnetic coordinates to prepare these data for analysis alongside other data sources.

2.3 Data Analysis

2.3.1 Geomagnetic Index Visibility Threshold

To assess the likelihood of auroral activity and visibility for Alaskan ports during the study period, the team conducted a statistical analysis of satellite-derived auroral precipitation data with geomagnetic indices. After initial processing to combine AE, Kp, and OP into the same CSV file, the data were refined to hours of darkness, 9 pm to 3 am Alaskan local time. They assessed the relationship between Kp and OP auroral intensity, as well as AE and OP, both contingent on latitude. After establishing that these relationships are non-linear between the indices and energy flux (measured in $\text{erg cm}^{-2} \text{s}^{-1}$), the team created box plots for three latitude bands (53.89-56.60°, 56.60-58.72°, and 58.72-61.18°) (Figure 3). These bands distribute the Alaskan port stops into three groups. With these box plots, the team calculated the weighted average Kp value for each latitude range. The OP flux threshold at which the human eye can detect aurora is $1.0 \text{ erg cm}^{-2} \text{s}^{-1}$ (Newell, et al., 2014). The team treated the average weighted Kp value as an equivalent critical value for each latitude range to make forecasts based on Kp. Dividing the number of Kp values for the months of August through October in a given previous SC year that surpassed this threshold by the total number of Kp values for that time-period yields probability values for visible auroral occurrence. The same process could be done to find the equivalent AE critical value and corresponding probabilities if time allowed.

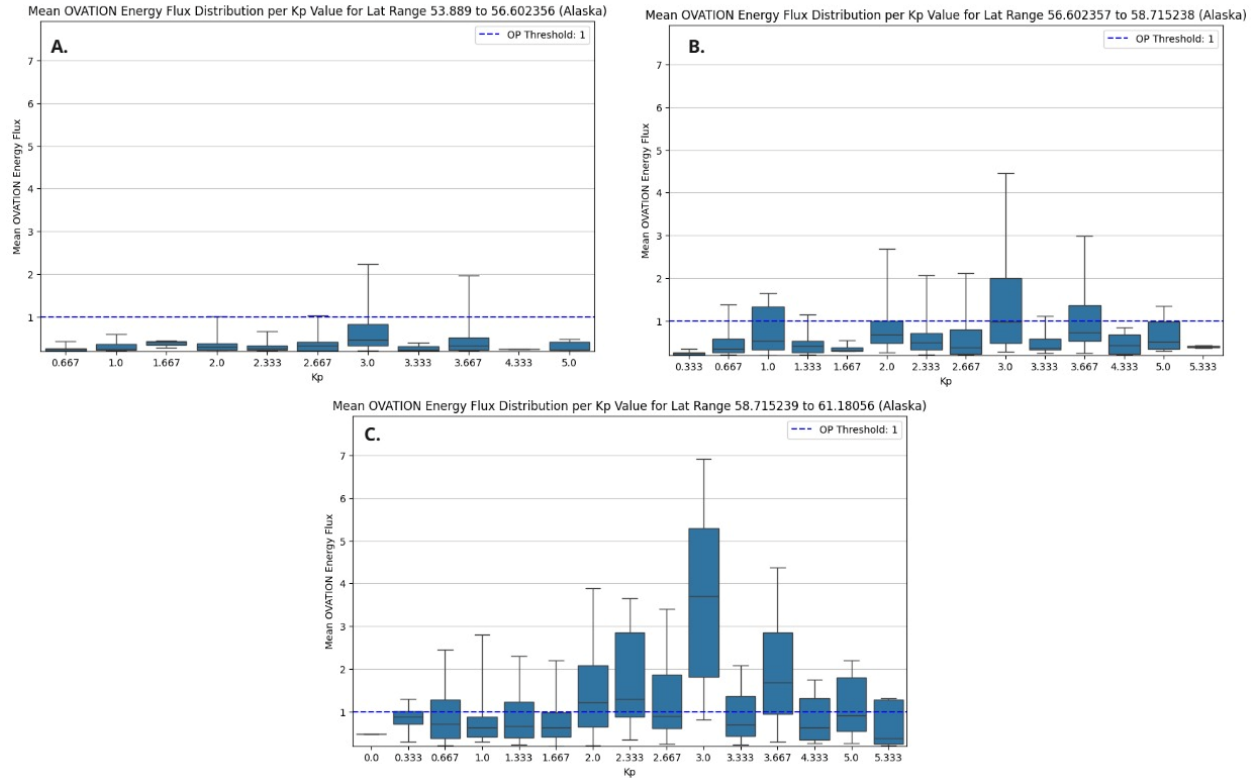


Figure 3. Boxplot analysis depicting the relationship between OVATION Prime energy flux values and Kp index to find the critical threshold value $1.0 \text{ ergs/cm s} = 1$ at which aurora occurrence is visible at various latitudinal bands within the study area. (a) low-latitudes (53.89°-56.60°), (b) mid-latitudes (56.60°-58.72°), and (c) highest latitudes (58.72°-61.18°).

The team analyzed OP data independent from index data to assess aurora visibility intensity alongside aurora occurrence and generated aurora visibility prediction values similarly to aurora occurrence values by identifying how often the threshold for visibility was exceeded for a given latitude range and year.

2.3.2 Geomagnetic and Solar Activity Correlation

The team visualized AE and Kp trends corresponding to the SC through comparisons with SSN patterns. Although the monthly averaged SSN data used in this project possess a coarser temporal resolution compared to AE and Kp indices (~ 1 hour), it provides essential context for understanding larger solar activity patterns. The team plotted the 11-year span of SSN for SCs 24 and 25, comparing the timescales to the maximum and ending minimum of the cycles and the overall cycle strength. This SSN analysis ensured that the use of data from the previous SC was an accurate proxy of comparison for the upcoming declining trend in solar activity.

3. Results

3.1 Analysis of Results

The analysis began with the comparison of SSN from SC 24 and SC 25, revealing that SC 25 was about 32.5% stronger than SC 24 and is projected to have a slightly longer decay phase. Overall, the two cycles follow a similar trend, consisting of double peaks around the time of maximum. Due to the unpredictability in the exact date of maxima, the team concluded an 11-year cycle trend was a realistic and accurate assumption for SC25. The team went ahead with correlating data from 11 years ago to the upcoming declining phase, including a strength adjustment of 32.5% to better represent the predicted cycle activity strength.

The Kp index showed corresponding trends with SC 24, with Kp values steadily increasing until the solar maximum and subsequently declining. Kp has a slight time lag relative to SSN (Figure 4). In exploring the relationship between OP data and the Kp index, the team identified a critical Kp threshold indicating aurora activity. The initial attempt of forecasting auroral activity based on a linear relationship between the energy flux values and Kp were insufficient due to the non-linear relationship between the data. A weighted average of Kp values for various latitude bands showed lower critical Kp thresholds at higher latitudes within the arctic polar region. The critical Kp threshold values were used to calculate the probability of auroral activity by latitude bands, which showed there is a higher aurora occurrence probability as latitude increases (Figure 5).

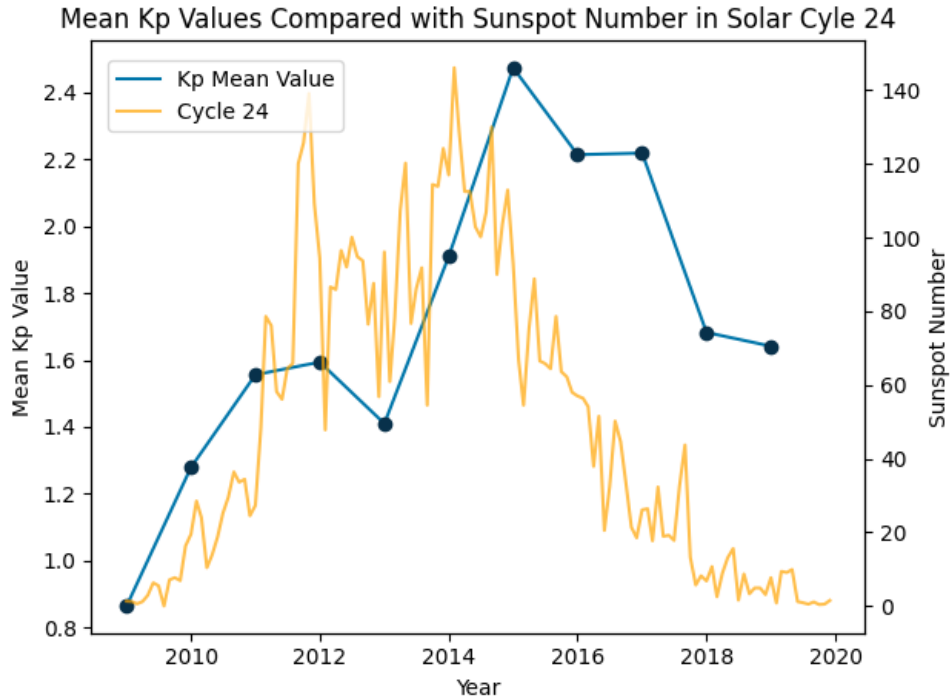


Figure 4. Mean Kp values compared to SSN within SC 24.

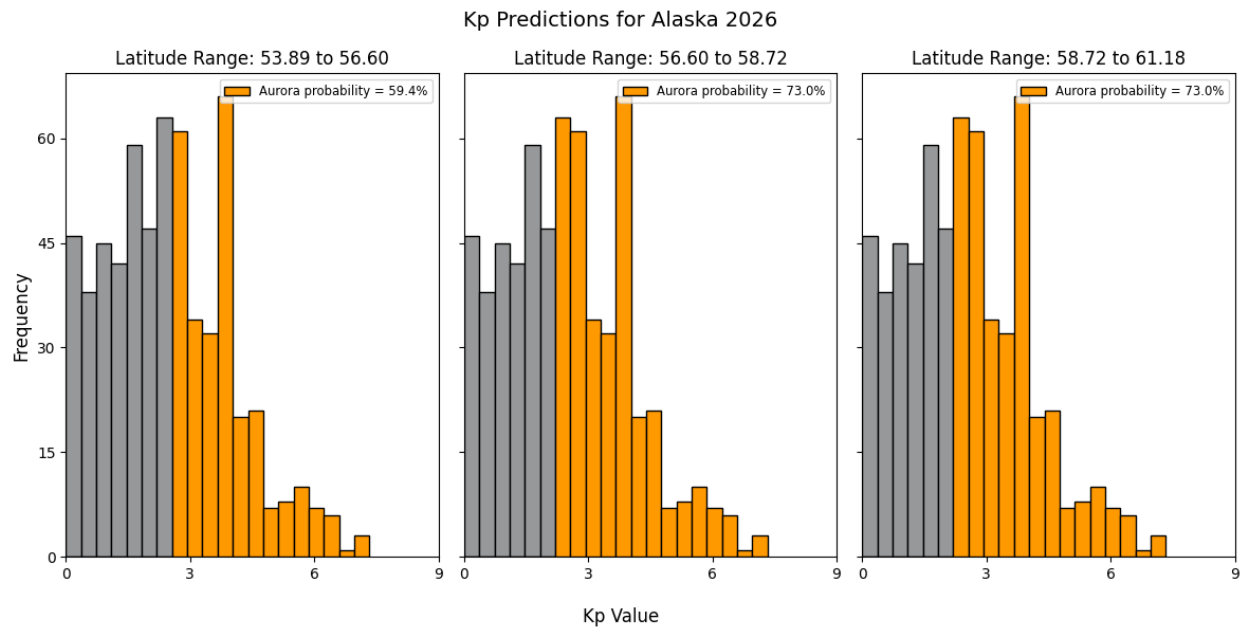


Figure 5. Kp values that meet the threshold for visible aurora highlighted in orange, binned by latitude. Lowest latitudes (53.89° - 56.60°) on the left, mid-latitudes (56.60° - 58.72°) in the middle, and highest latitudes (58.72° - 61.18°) on the right.

The team analyzed OP energy flux data to provide further insight into aurora visibility and yielded reliable results for predicting location and auroral intensity. Analysis of historical OVATION data for the study

period showed increasing energy flux corresponding to higher latitudes. This aligns with established knowledge that auroral activity increases with latitude.

The team made a preliminary probability map showing the likelihood of aurora occurrence based on the relationship between OP and Kp (Figure A1), as well as a map showing the probability of intense aurora (i.e. aurora visibility) based on the OP probability. They show probability values for all Alaskan port stops corresponding to their latitude range in the map key (Figure 6).

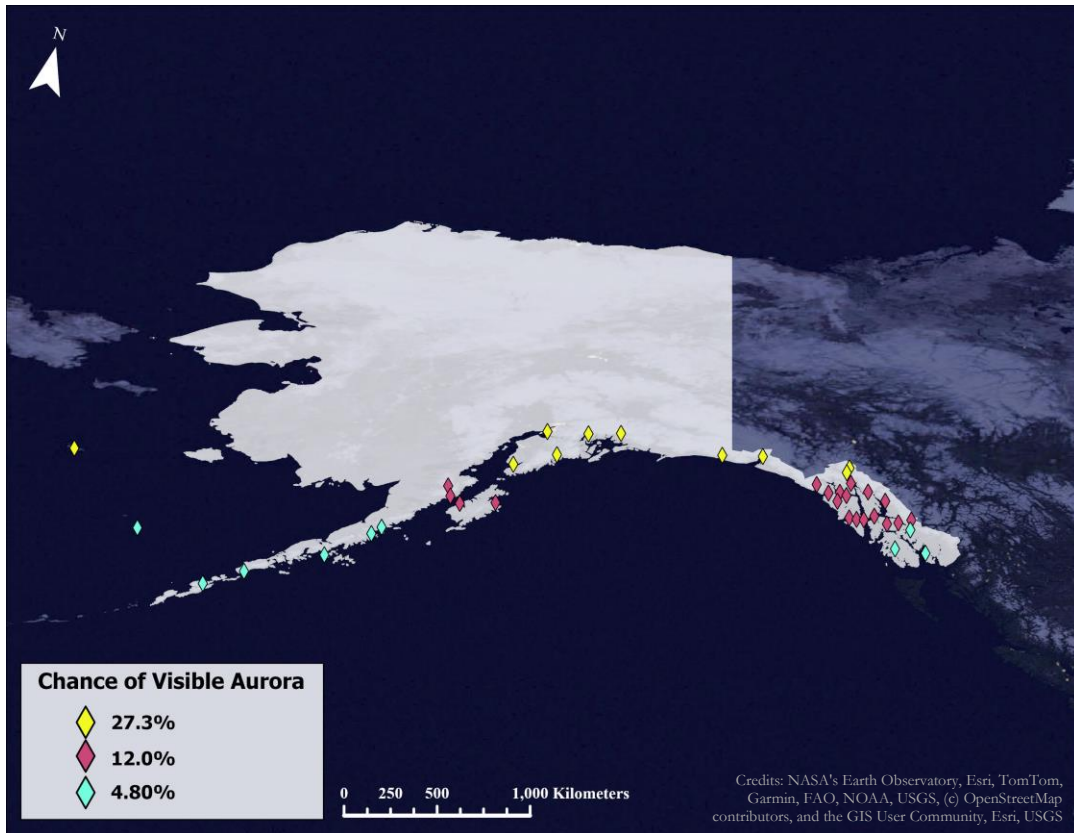


Figure 6. Chance of viewing intense, visible aurora at Alaskan port stops, forecasted into 2026

3.2 Errors & Uncertainties

Intense temporal, spatial, and data processing demands were a significant cause for errors and uncertainties within this study. The team discovered later in the project that there was significant data loss for 2017 OP data. As the team created our own downloading and processing programming, this may be the source of the error if there was a miscalculation when rescaling the temporal and spatial resolution. The error could also have originated directly from the unexpected crashes of OP runs at CCMC website.

For the case study, the image of VIIRS-observed aurora overlayed onto the OP energy flux output shows a slight misalignment in the resulting location of the directly observed and predicted aurora. The VIIRS aurora appears slightly lower than the highest OP-produced energy flux values. It would be helpful to run a number of case studies to see if OP consistently underestimates the equatorward boundary of the predicted aurora when compared to directly observed aurora.

The team attempted to find a linear relationship between the OP energy flux values and geomagnetic activity indices (using both Kp and AE). The resulting relationship did not follow a linear trend, and rather appeared to be more Gaussian in nature, with mid-range geomagnetic index values having the highest average weighted value, and low and high-range values showing lower average weighted values.

To maximize efficiency, the team only analyzed historical data from SC 24 and used a strength adjustment to make the relatively weak SC 24 match the current SC 25 activity. Alongside this adjustment, the team made the assumption that SC 25 follows an exact 11-year trend with consistent timing between the time of maximum and minimum activity. They determined this assumption was reasonable due to the added double-peak uncertainty around the time of maximum, but the accuracy of SC comparison results could be further strengthened if multiple cycles could have been included into the comparison trend. Analyzing additional SCs would provide more historic data for a better reliable trend for forecasting future auroral phenomena.

4. Conclusions

4.1 Interpretation of Results

This research demonstrates a logical workflow to utilize NASA's Earth observation data, geomagnetic indices, and an aurora prediction model to produce a statistical prediction of auroral occurrence throughout the Alaska region. We have demonstrated that the Suomi-NPP satellite equipped with the VIIRS DNB sensor can provide auroral observations to validate the OP model based on historical performance. Upon successful validation, this model can be utilized for the study and forecasting of aurora.

The OP model demonstrates potential for long term aurora occurrence prediction when combined with geomagnetic indices, such as Kp, assuming similar solar driver and geospace response between various SCs of interest. Analyzing historical OP data on its own demonstrates potential for forecasting auroral intensity upon occurrence, not accounting for cloud cover, light pollution, or other potential optical obstructions unassociated with geomagnetic activity. Predictive forecasting efforts produce a spatiotemporal guide to potential aurora occurrence and visibility for future voyages. Engagements with TPAC throughout this study and the sharing of results served to enhance partner and passenger understanding of auroral phenomenon.

Using NASA Earth observation data, measures of geomagnetism, and aurora prediction models provide verifiable workflow for producing long-term aurora predictions that improve the understanding of aurora as well as near and short-term aurora predictions.

4.2 Feasibility & Partner Implementation

Overall, the team determined that it was possible to utilize remote sensing Earth observations, predictive model applications, and historical geomagnetic activity data to forecast potential auroral visibility during coming polar tourism seasons. Additionally, utilizing SSN of SC 24 as a proxy for SC 25 was deemed feasible with the proper strength adjustment techniques applied. However, applications of this method were unfeasible for including previous SCs nor to apply to Arctic port stops outside of the Alaskan region due to project 10-week timeline constraints. Applications to other regions such as Greenland are feasible without time constraints.

Understanding periods of potential auroral activity is important for TPAC to implement into cruise planning and strategy. Understanding periods of potential high auroral visibility allows TPAC to market auroral watch cruises to passengers and potentially grow in interest and revenue on future cruises. Additionally, the project benefits both TPAC and passenger's understanding of both Space Weather and aurora occurrence through generated discussion, educational materials, and encouragement of citizen science participation aboard the cruise. TPAC has the potential to apply this project and its methodologies to additional port stops in the Arctic region and potential analysis of the Antarctic region.

4.3 Limitations

The team encountered several limitations throughout the course of the project. The first is due to general observational obstructions of the auroras. Certain natural phenomena can impede aurora visibility such as weather (i.e. cloud cover) and full moon light pollution. The VIIRS instrument has cloud masking capabilities which will remove any data of the aurora obstructed by clouds, but this in turn eliminated observations from several days within the study period and limited the number of direct observations that could be used for

validating OP output. The team additionally hoped to better implement citizen science data into the project, but Aurorasaurus had very few reported sightings during our specific case study period.

The second limitation emerged from the opposite issue: too much data and limited storage and processing power. The OP model output data every five minutes covering the entire Arctic Circle. When running the model for the decline phase of SC 25, the team ran into data loss issues. The NASA-provided computers were storage-limited and faced extreme run-times when attempting to download such large quantities of information. Leveraging cloud storage and computing capabilities such as at Amazon Web Services could be a solution to this limitation.

The final major limitation relates to the number of instruments directly observing auroral phenomena. Previous projects have been unsuccessful in discerning auroral observations alone from VIIRS imagery as it is a relatively challenging task. The team was successful in extracting auroral granules, however many of the daily images, especially during the period of study, were blocked by cloud cover.

Fortunately, the Electrojet Zeeman Imaging Explorer (EZIE) was just launched in March 2025 with the sole purpose of measuring auroral currents in the upper atmosphere at Earth's poles. A coinciding citizen science project, EZIE-Mag, provides the public with magnetometers to validate EZIE data through ground-based measurements. Both EZIE and EZIE-MAG will provide valuable information to better understand and predict aurora for community needs.

6. Glossary

ACE – Advanced Composition Explorer

Suomi NPP VIIRS DNB – Suomi National Polar-orbiting Partnership Visible Infrared Imaging Radiometer Suite Day/Night Band

Magnetic reconnection – Where magnetic field lines in plasma both break and reconnect, releasing energy and accelerating charged particles

Magnetosphere – The region where a magnetic field surrounds a planetary body

Magnetosheath – The space between the magnetopause and the bow shock of a planet's magnetosphere

Coronal holes – Parts of the Sun's corona that emit low ultra-violet radiation compared to its surroundings

Corona – The outermost part of the Sun's atmosphere

Plasma – A state of matter that consist of charged particles

Lagrange point – The point where the gravitational pull of two large masses is equal to keeping a small object to stay put.

Auroral Electrojet index (AE) – a gauge of high-latitude currents flowing from the magnetosphere into the auroral zone of the Earth's ionosphere

Planetary K-index (Kp) – Combines measurements of magnetic variability from individual magnetometers to scale geomagnetic disturbance in Earth's magnetic field and is used to categorize global aurora likelihood in this project

Ionosphere – A layer of electrons in Earth's upper atmosphere, created by solar radiation and other phenomena

Auroral electrojets – The ionospheric component of current systems through which the outer magnetosphere is coupled to the ionosphere

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8. Appendices

Appendix A: Alaskan Port Stops

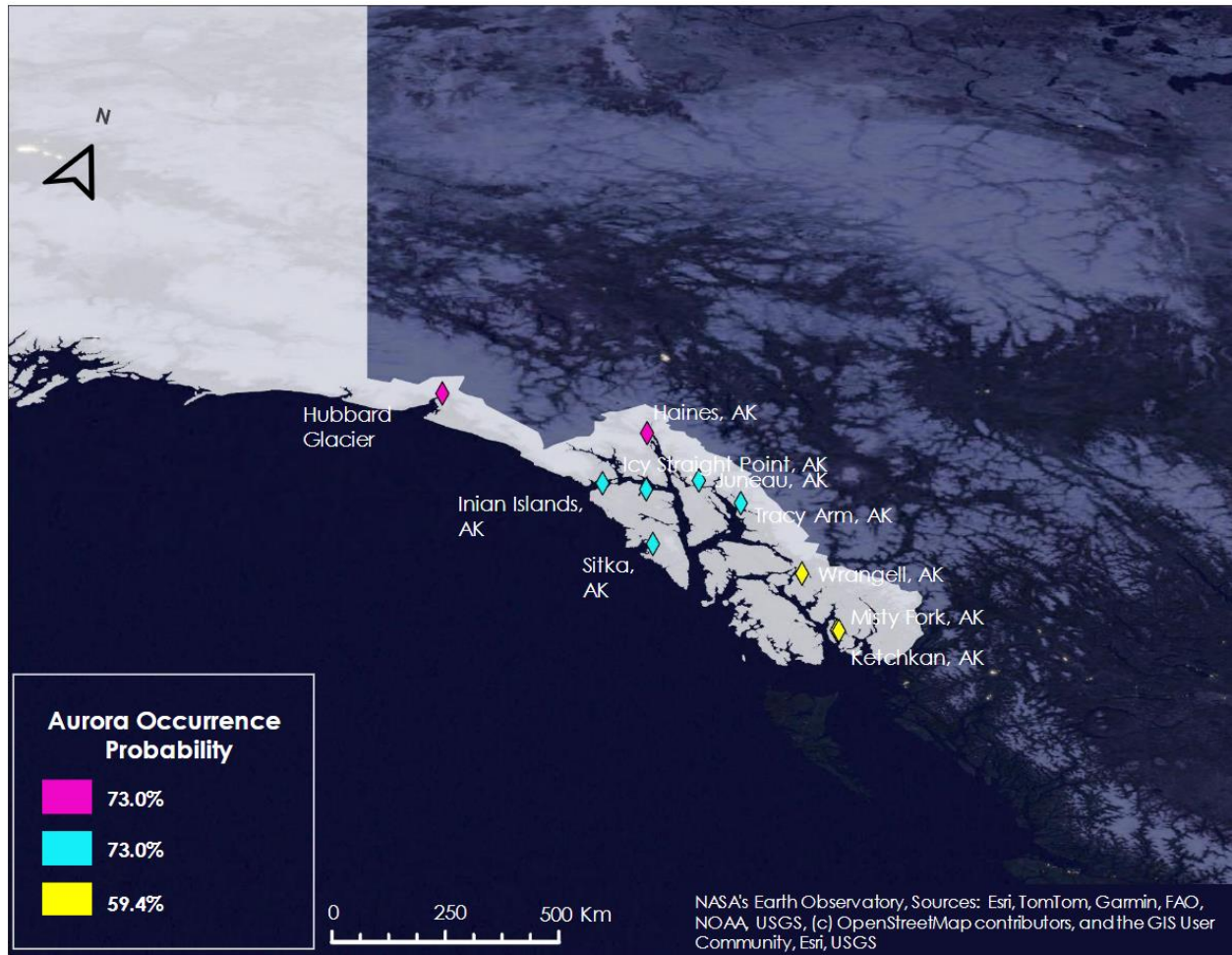


Figure A1. Chance of observing aurora at Alaskan port stops of Expedition Cruise of 2026.