21-Year Modeled Spatiotemporal Low-Level Jet Climatology Along the U.S. Mid-Atlantic Coast

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Pacific Northwest NATIONAL LABORATORY

WFIP-3 Multi-Lab-Univ Team

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OOI OCEAN OBSERVATORIES INITIATIVE

RWSC Regional Wildlife Science Collaborative for Offshore Wind

ROSA Responsible Offshore Science Alliance

Project Websites:

https://www2.whoi.edu/site/wfip3

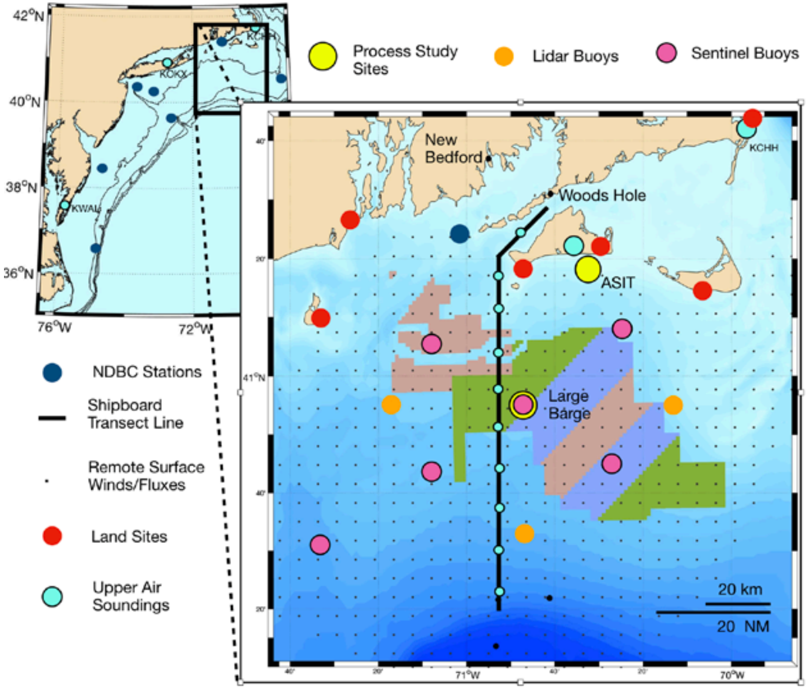
https://www.pnnl.gov/projects/wind-forecast-improvement-project-3

https://a2e.energy.gov/project/wfip3

WFIP-3 Expected Outcomes

- 18-month-long publicly available high-resolution offshore data (starting January 2024)
- Improved wind forecasting skill of the region
  - Develop new boundary layer and surface layer parameterizations to be implemented in NOAA's RRFSv2 model
- Quantify which modeling developments (coupled modeling, improved PBL, improved surface layer, etc.) yield the largest impact on reducing the LCOE for offshore wind in the U.S.

Observations → Modeling Improvements → Industry Products



6 land sites

10-element mooring array

2 process study Sites

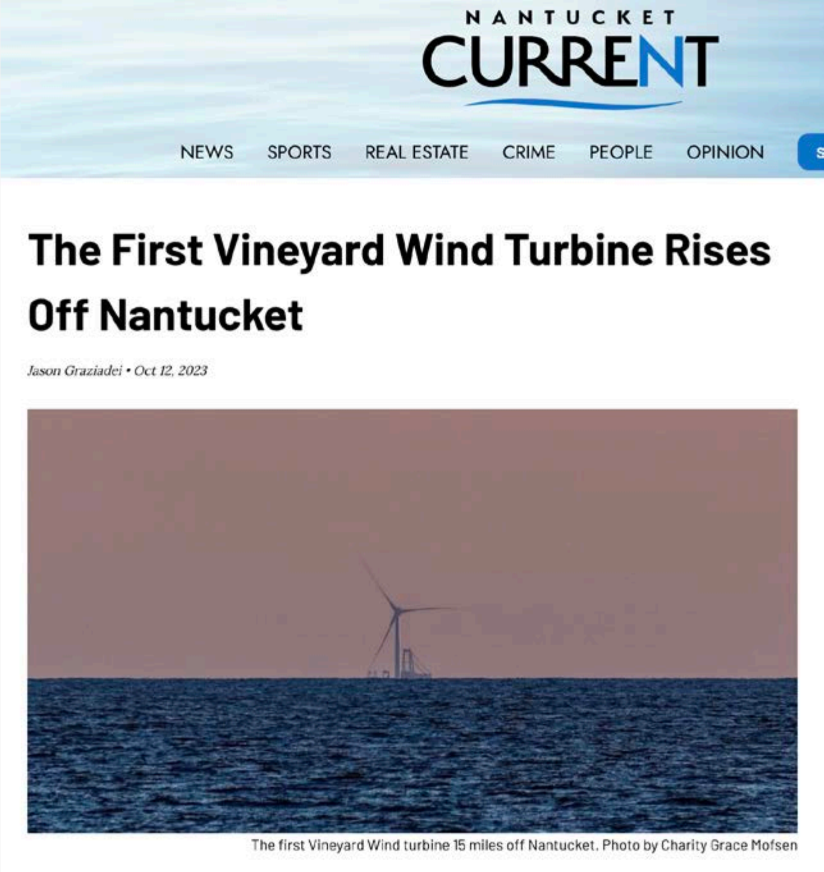
Remote sensing via high-frequency radar and satellite

LCOE = levelized cost of energy; PBL = planetary boundary layer; NOAA = National Oceanic and Atmospheric Administration

Background/Motivation

Why do we care about modeled low-level jet climatologies?

A new dawn…



NANTUCKET CURRENT

NEWS SPORTS REAL ESTATE CRIME PEOPLE OPINION

The First Vineyard Wind Turbine Rises Off Nantucket

Jason Graziadei • Oct 12, 2023

The first Vineyard Wind turbine 15 miles off Nantucket. Photo by Charity Grace Mofsen

https://www.vineyardwind.com/press-releases/2023/10/18/avangrid-cip-announce-successful-installation-of-the-first-turbine-for-vineyard-wind-1

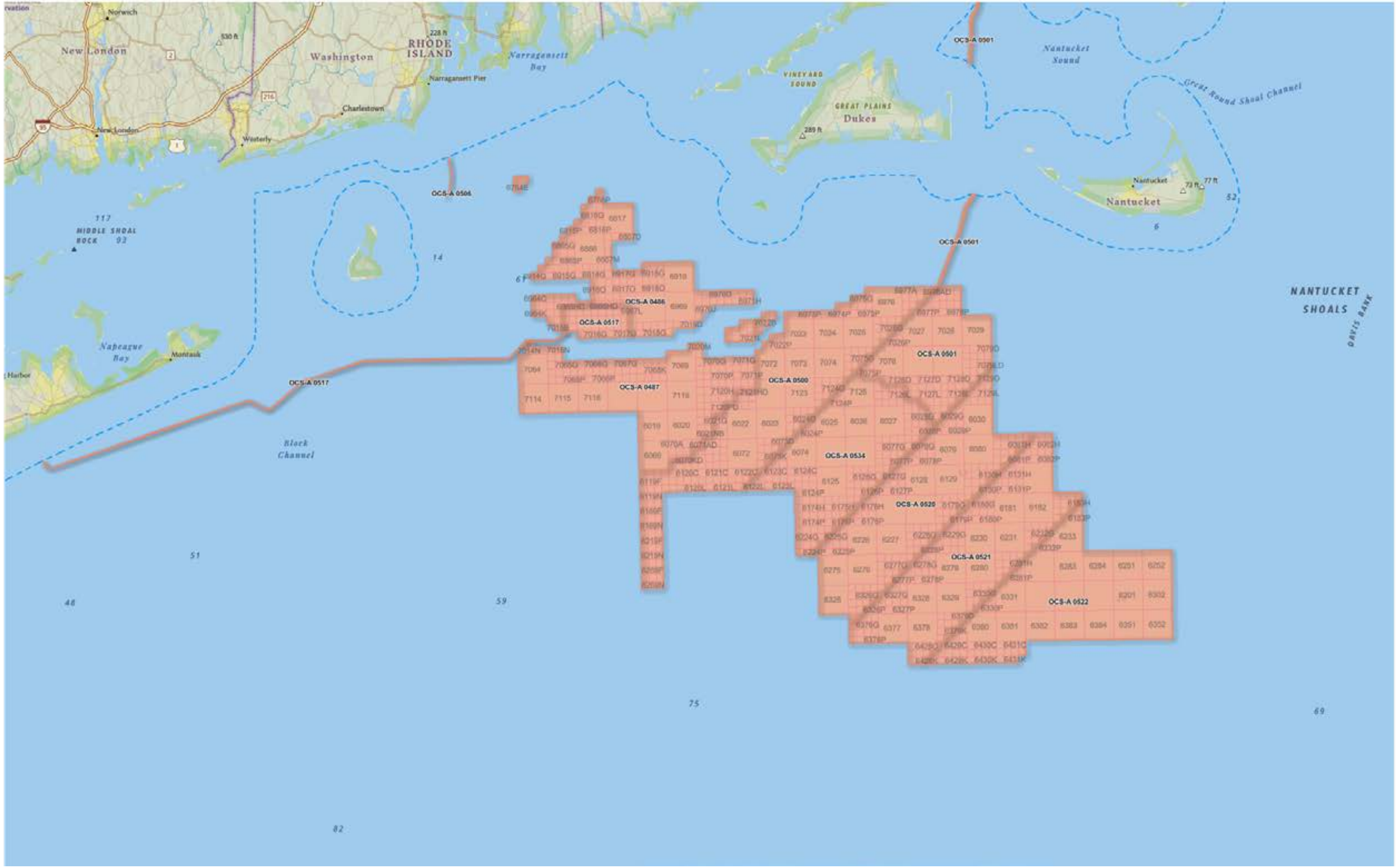
https://nantucketcurrent.com/news/first-vineyard-wind-turbine-rises-off-nantucket

Why do we care about low-level jets?

- Low-level jets (LLJs) can have large impacts on power production (Kelley et al. 2004).
  - Ramps, ability to forecast, etc.
- Changes in wind speed and direction across the rotor layer impose structural stress on the wind turbine (Kelley, Jonkman, and Scott 2006).
  - Offshore turbines are taller and have longer rotor diameters, increasing the likelihood of LLJ impacts.
- While impactful, there is no agreed-upon definition of what constitutes an LLJ.
  - Different definitions lead to different results.

Regions of Interest

Focus on the Rhode Island/Massachusetts wind energy areas



Norwich
New London
Washington
RHODE ISLAND
Narragansett Bay
Narragansett Pier
Charlestown
Westerly
VINEYARD SOUND
GREAT PLAINS
Dukes
Nantucket Sound
Great Round Shoal Channel
Nantucket
NANTUCKET SHOALS
DAVIS BANK
MIDDLE SHOAL ROCK
Napeague Bay
Montauk
Block Channel
OCS-A 0506
OCS-A 0517
OCS-A 0486
OCS-A 0487
OCS-A 0500
OCS-A 0501
OCS-A 0534
OCS-A 0520
OCS-A 0521
OCS-A 0522

The NOW-23 Dataset

Next-generation offshore wind resource dataset

Map from https://data.openei.org/submissions/4500

NOW-23 domains and characteristics

- 21-year (2000–2020) Weather Research and Forecasting (WRF) model
- 2-km spatial resolution
- 5-minute or hourly temporal resolution
- Variables, such as wind speed and direction, saved up to 500 m, with a 20-m vertical resolution (up to 300 m).

Low-Level Jet Definition

How do we define an LLJ?

Long History of LLJ Study and Definition

October 2005 SONG ET AL. 1593

Climatology of the Low-Level Jet at the Southern Great Plains Atmospheric Boundary Layer Experiments Site

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RICHARD L. COULTER AND BARRY M. LESHT
Environmental Research Division, Argonne National Laboratory, Argonne, Illinois

(Manuscript received 18 October 2004, in final form 22 April 2005)

ABSTRACT

A unique dataset obtained with combinations of minisodars and 915-MHz wind profilers at the Atmo-

energies MDPI

Article

Occurrence of Low-Level Jets over the Eastern U.S. Coastal Zone at Heights Relevant to Wind Energy

Jeanie A. Aird [1,*], Rebecca J. Barthelmie [1], Tristan J. Shepherd [2] and Sara C. Pryor [2]

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Abstract: Two years of high-resolution simulations conducted with the Weather Research and Forecasting (WRF) model are used to characterize the frequency, intensity and height of low-level jets (LLJ) over the U.S. Atlantic coastal zone. Meteorological conditions and the occurrence and characteristics of LLJs are described for (i) the centroids of thirteen of the sixteen active offshore wind energy lease areas off the U.S. east coast and (ii) along two transects extending east from the U.S. coastline across the northern lease areas (LA). Flow close to the nominal hub-height of wind turbines is predominantly northwesterly and southwesterly and exhibits pronounced seasonality, with highest wind speeds in November, and lowest wind speeds in June. LLJs diagnosed using vertical profiles of modeled wind speeds from approximately 20 to 530 m above sea level exhibit highest frequency in LA south of Massachusetts, where LLJs are identified in up to 12% of hours in June. LLJs are considerably less frequent further south along the U.S. east coast and outside of the summer season. LLJs frequently occur at heights that intersect the wind turbine rotor plane, and at wind speeds within typical wind turbine operating ranges. LLJs are most frequent, intense and have lowest core heights under strong horizontal temperature gradients and lower planetary boundary layer heights.

check for updates

Citation: Aird, J.A.; Barthelmie, R.J.; Shepherd, T.J.; Pryor, S.C. Occurrence of Low-Level Jets over the Eastern U.S. Coastal Zone at Heights

Wind Energ. Sci., 6, 1043–1059, 2021
https://doi.org/10.5194/wes-6-1043-2021

eawe WIND ENERGY SCIENCE

Extreme wind shear events in US offshore wind energy areas and the role of induced stratification

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Received: 2 September 2020 – Discussion started: 17 September 2020
Revised: 13 May 2021 – Accepted: 4 June 2021 – Published: 10 August 2021

Abstract. As the offshore wind industry emerges on the US East Coast, a comprehensive understanding of the wind resource – particularly extreme events – is vital to the industry's success. Such understanding has been hindered by a lack of publicly available wind profile observations in offshore wind energy areas. However, the New York State Energy Research and Development Authority recently funded the deployment of two floating lidars within two current lease areas off the coast of New Jersey. These floating lidars provide publicly available wind speed data from 20 to 200 m height with a 20 m vertical resolution. In this study, we leverage a year of

June 2015 VANDERWENDE ET AL. 2319

Observing and Simulating the Summertime Low-Level Jet in Central Iowa

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(Manuscript received 9 October 2014, in final form 19 February 2015)

ABSTRACT

In the U.S. state of Iowa, the increase in wind power production has motivated interest into the impacts of low-level jets on turbine performance. In this study, two commercial lidar systems were used to sample wind profiles in August 2013. Jets were systematically detected and assigned an intensity rating from 0 (weak) to 3 (strong). Many similarities were found between observed jets and the well-studied Great Plains low-level jet in summer, including average jet heights between 300 and 500 m above ground level, a preference for southerly wind directions, and a nighttime bias for stronger jets. Strong vertical wind shear and veer were observed, as well as veering over time associated with the LLJs. Speed, shear, and veer increases extended into the turbine-rotor layer during intense jets. Ramp events, in which winds rapidly increase or decrease in the rotor layer, were also commonly observed during jet formation periods. The lidar data were also used to evaluate various configurations of the Weather Research and Forecasting Model. Jet occurrence exhibited a stronger dependence on the choice of initial and boundary condition data, while reproduction of the strongest jets was influenced more strongly by the choice of planetary boundary layer scheme. A decomposition of mean model winds suggested that the main forcing mechanism for observed jets was the inertial oscillation. These results have implications for wind energy forecasting and site assessment in the Midwest.

MONTHLY WEATHER REVIEW
VOLUME 96, NUMBER 12
DECEMBER 1968

CLIMATOLOGY OF THE LOW LEVEL JET

WILLIAM D. BONNER
Department of Meteorology, University of California at Los Angeles, Calif.

ABSTRACT

Geographical and diurnal variations in the frequency of occurrence of strong low level wind maxima are determined using 2 yr. of wind data from 47 rawinsonde stations in the United States. Maximum frequency of occurrence is found in the Great Plains at approximately 37°N. and 98°W. The vast majority of jets in this region occur with southerly flow. Southerly wind maxima appear on both morning and afternoon soundings but occur with much greater frequency, over a larger area, on the morning observations.

Twenty-eight morning jet cases are used to determine average synoptic-scale wind and temperature patterns in the vicinity of the jet. Diurnal wind oscillations are examined by comparisons of jet frequencies, speeds, and altitudes on four-times-daily observations. The oscillation is similar to that described by Blackadar; however, there is no apparent tendency for the latitudinal variation in period of the oscillation which Blackadar's model implies.

October 1997 WHITEMAN ET AL. 1363

Low-Level Jet Climatology from Enhanced Rawinsonde Observations at a Site in the Southern Great Plains

C. DAVID WHITEMAN, XINDI BIAN, AND SHIYUAN ZHONG
Pacific Northwest National Laboratory, Richland, Washington

(Manuscript received 18 February 1997, in final form 7 April 1997)

ABSTRACT

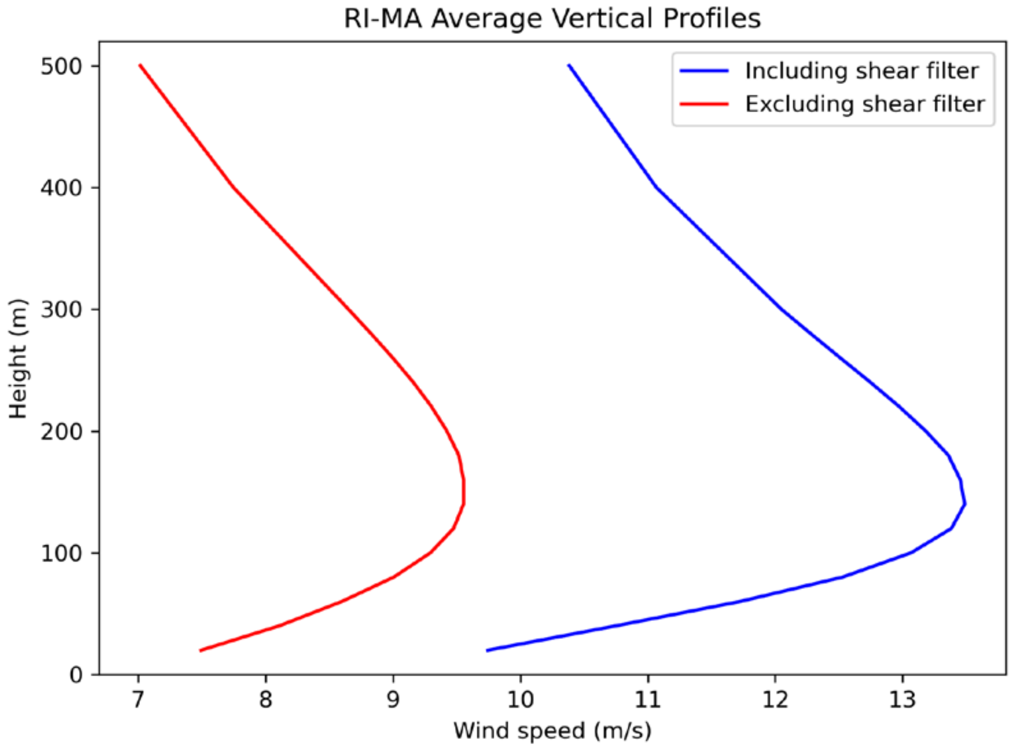
A climatology of the Great Plains low-level jet (LLJ) is developed from 2 yr of research rawinsonde data obtained up to eight times per day at a site in north-central Oklahoma. These data have better height and time resolution than earlier studies, and show that jets are stronger than previously reported and that the heights of maximum wind speed are closer to the ground. LLJs are present in 47% of the warm season soundings and 45% of the cold season soundings. More than 50% of the LLJs have wind maxima below 500 m above ground level (AGL). Because the 404-MHz radar profiler network in the central United States has its first data points at 500 m AGL, it is likely to miss some LLJ events and will have inadequate vertical resolution of LLJ wind structure.

Previous studies have identified LLJs on the basis of a wind speed profile criterion. This criterion fails to separate the classical southerly LLJs from the less frequent northerly jets, which differ in both structure and evolution. Classical southerly jets are more frequent; they occur year round, with the highest frequency in the summer and at night. Southerly LLJ wind speed maxima are most frequently found at 300–600 m AGL, and peak speeds, typically between 15 and 21 m s^{-1}, are attained at 0200 CST. The height of the wind speed maximum varies little during nighttime—a period when surface-based inversions grow in depth but generally remain below the jet. Winds at the nose of the southerly jets exhibit a distinct diurnal clockwise turning in wind direction and an oscillation in speed.

Northerly jets occur year round. They are generally associated with cold air outbreaks and are found in the cold air behind southward-moving cold fronts. In winter, their frequency of occurrence rivals that of the southerly jets. Their occurrence, however, is less dependent on time of day, with a weak daytime maximum. They are more variable in the heights of their wind speed maxima, are associated more frequently with elevated frontal inversions, and do not exhibit a clockwise turning with time. The heights of the jet speed maxima are found to increase with distance behind the surface cold front.

LLJ Definition

- Criteria used:
  - Minimum wind speed at 150 m > 3 m/s.
  - LLJ cannot be at the lowest/highest NOW-23 altitudes (20 and 500 m, respectively).
  - Drop in wind speed above the nose ≥ 1.5 m/s and ≥ 10%.
  - Criterion 2 from Debnath et al. (2021) dropped (wind shear gradient minimum in the rotor layer).

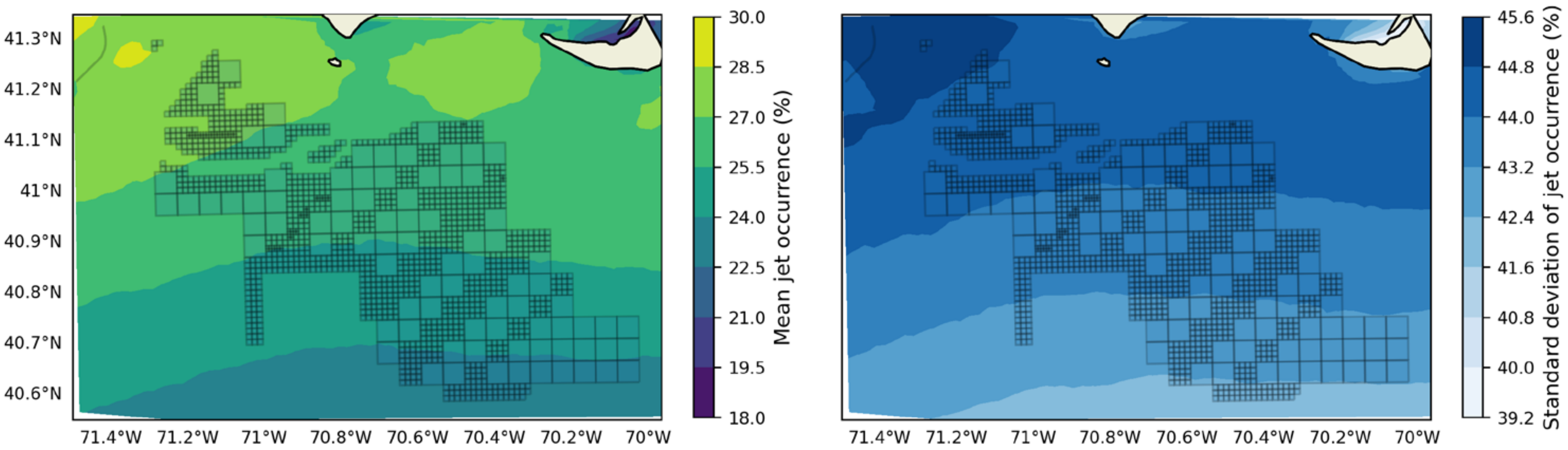


LLJ Characteristics

- Four characteristics used in this study:
  - Percent of jet occurrence: percentage of time that an LLJ is said to be occurring.
  - Nose height: height of the LLJ nose, where wind speeds are at their highest.
  - Nose top: height of where the LLJ has its lowest wind speeds above the nose height.
  - Nose speed: wind speed of the LLJ nose.

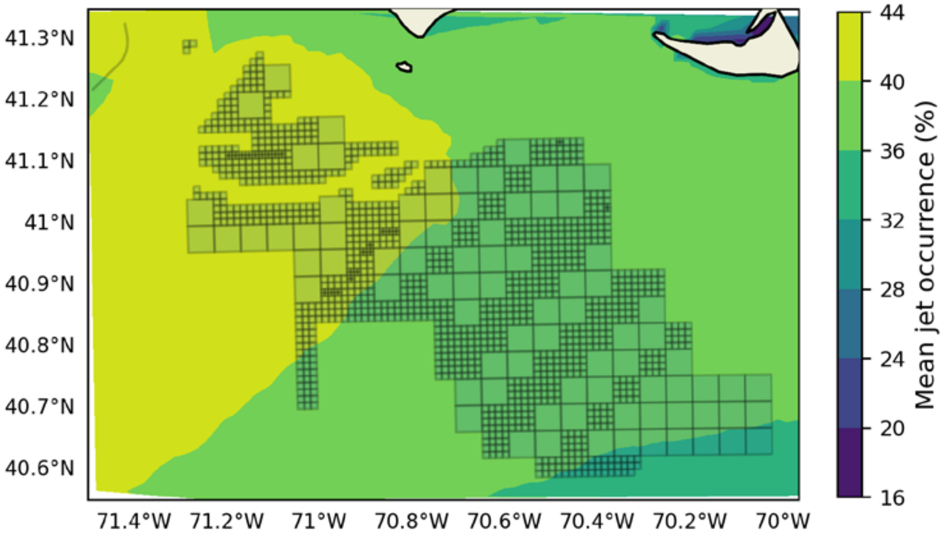
Spatial LLJ Climatology

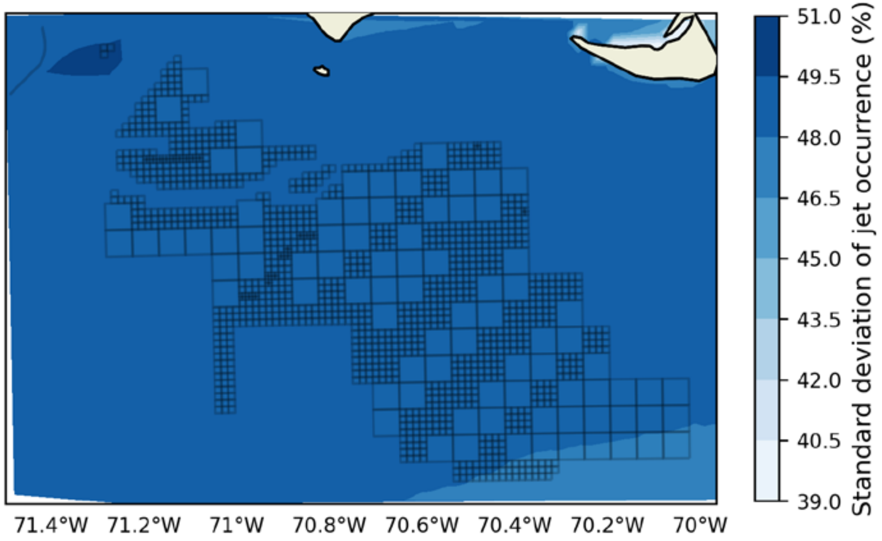
How do LLJs vary in the Rhode Island/Massachusetts wind energy areas?



Rhode Island – Mass. (All Conditions)

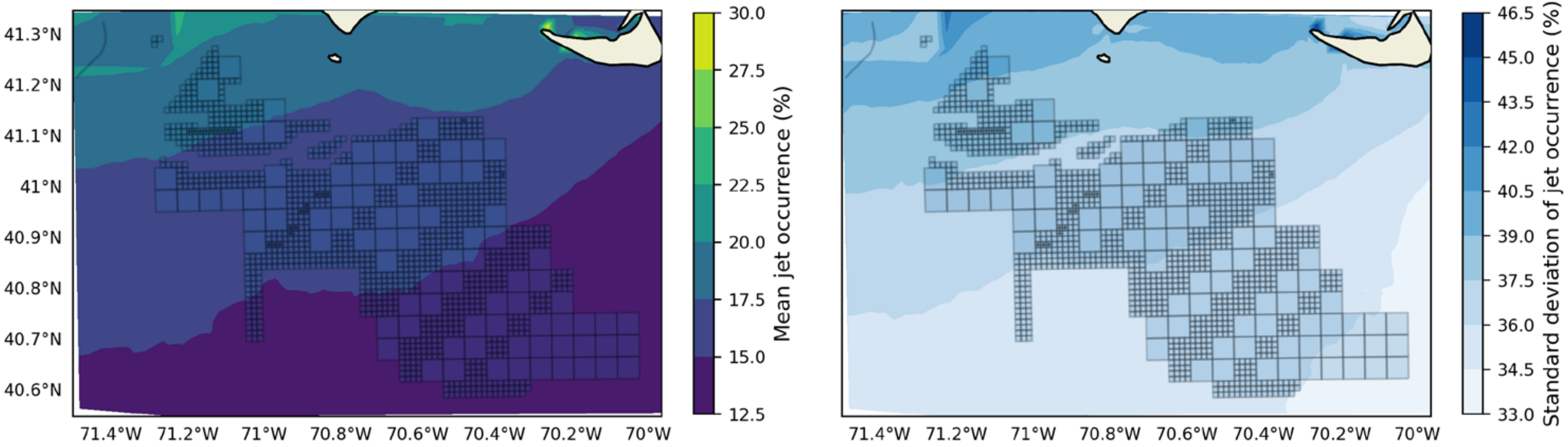
- ~26% LLJ activity in any given hour.
- ~6% spatial variability across the region.
- Higher LLJ activity in WNW.





Rhode Island – Mass. (Stable Conditions)

- ~39% mean LLJ activity.
- ~10% spatial variability across the region.
- Higher LLJ activity in the WNW.



Rhode Island – Mass. (Unstable Conditions)

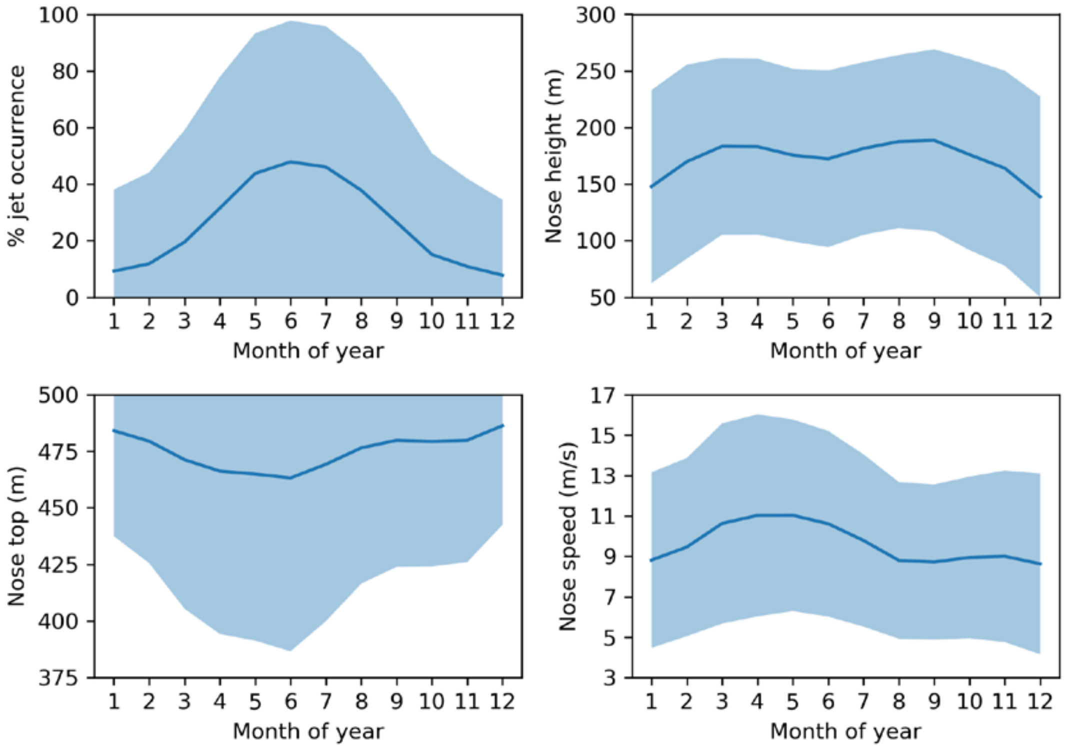
- ~16% mean LLJ activity.
- ~12% spatial variability across the region.
- Higher LLJ activity in the NW.

Temporal LLJ Climatology

Diurnal, monthly, and interannual behavior

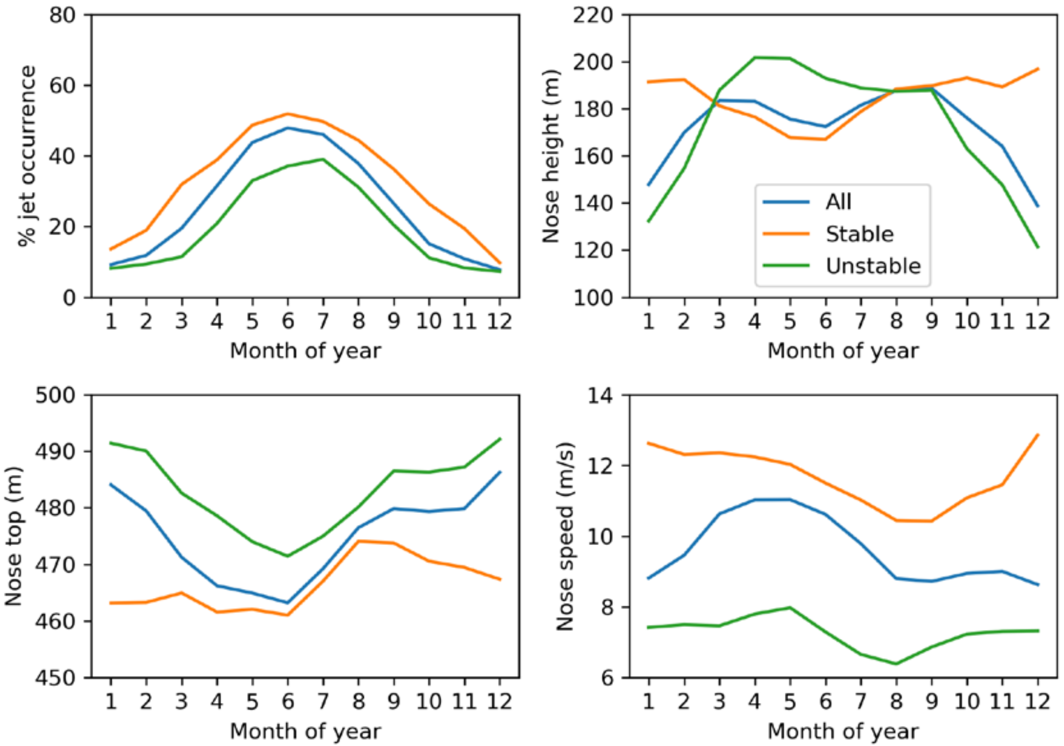
LLJ Characteristics Have Large Monthly Variability

- June has the highest LLJ activity while December has the lowest.
- LLJ nose heights are highest in September, lowest in December.
- LLJ nose tops are highest in December, lowest in June.
- Nose speeds of LLJs peak in May and are slowest in December.



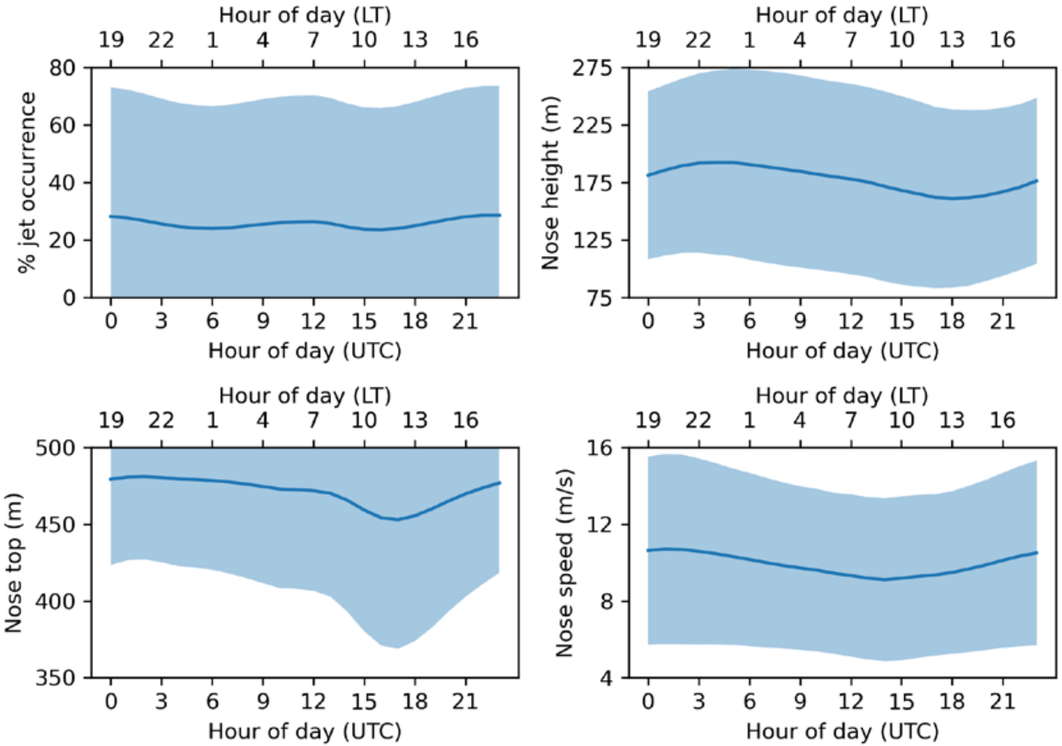
Monthly LLJs by Stability Tell Different Stories

- Stable conditions exhibit higher jet occurrence year-round.
- Nose heights appear bimodal, but peak at different times of the year.
- Nose tops are highest in the winter, lowest in early summer.
- Nose speeds are slowest in winter for unstable, but highest for stable.



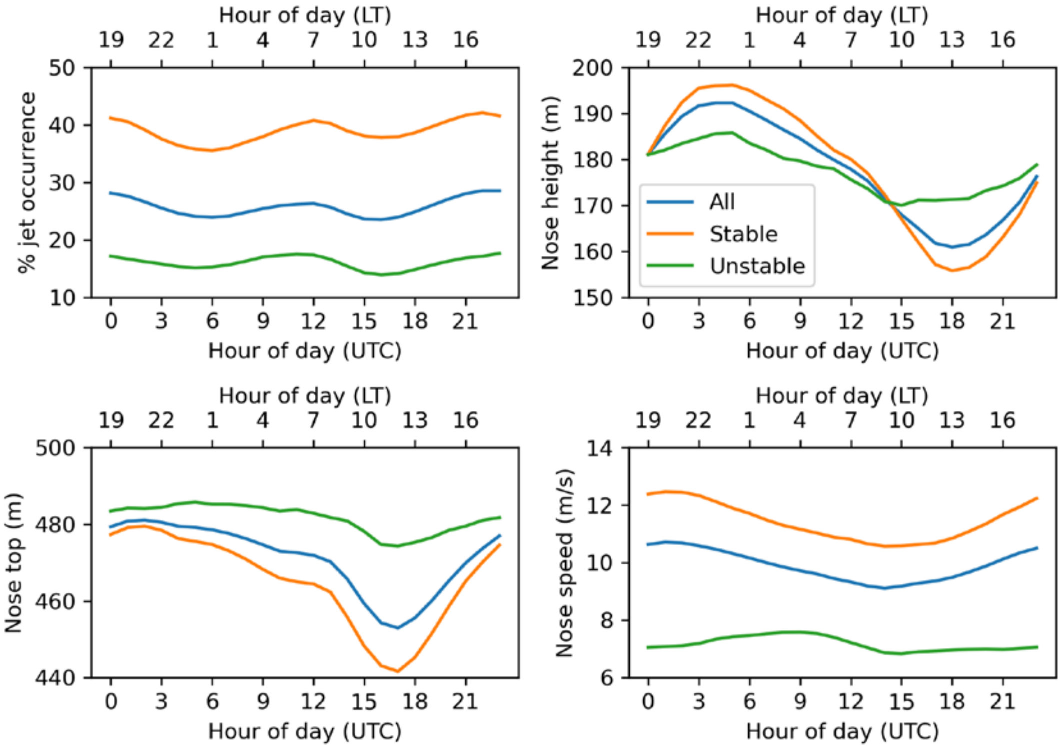
Weak Mean Diurnal Cycle Variability

- Slight bimodal jet occurrence, with peaks in the afternoon and morning.
- Large variability around the mean, with mean LLJ occurrence between 20% and 25%.
- Other factors likely at play with a muted diurnal response over water (e.g., wind direction).



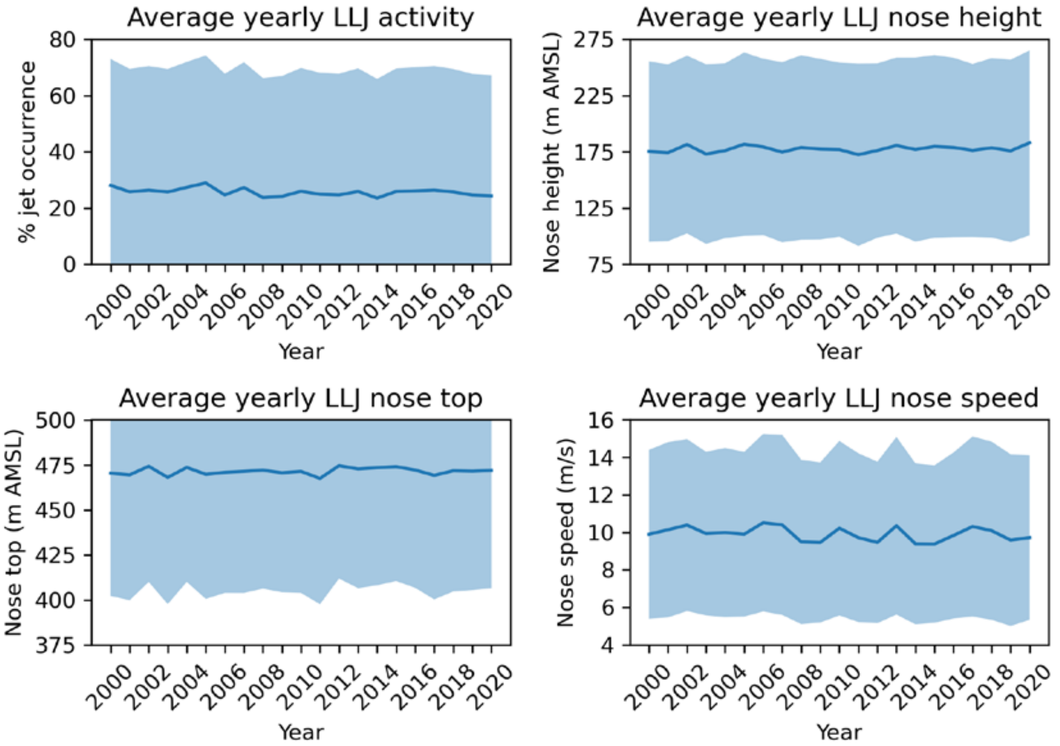
Large Differences in the Diurnal Cycle w.r.t. Stability

- Higher jet occurrence in stable conditions.
- Larger nose height fluctuations in stable conditions than unstable conditions.
- Higher nose tops in unstable conditions.
- Faster nose speeds in stable conditions.



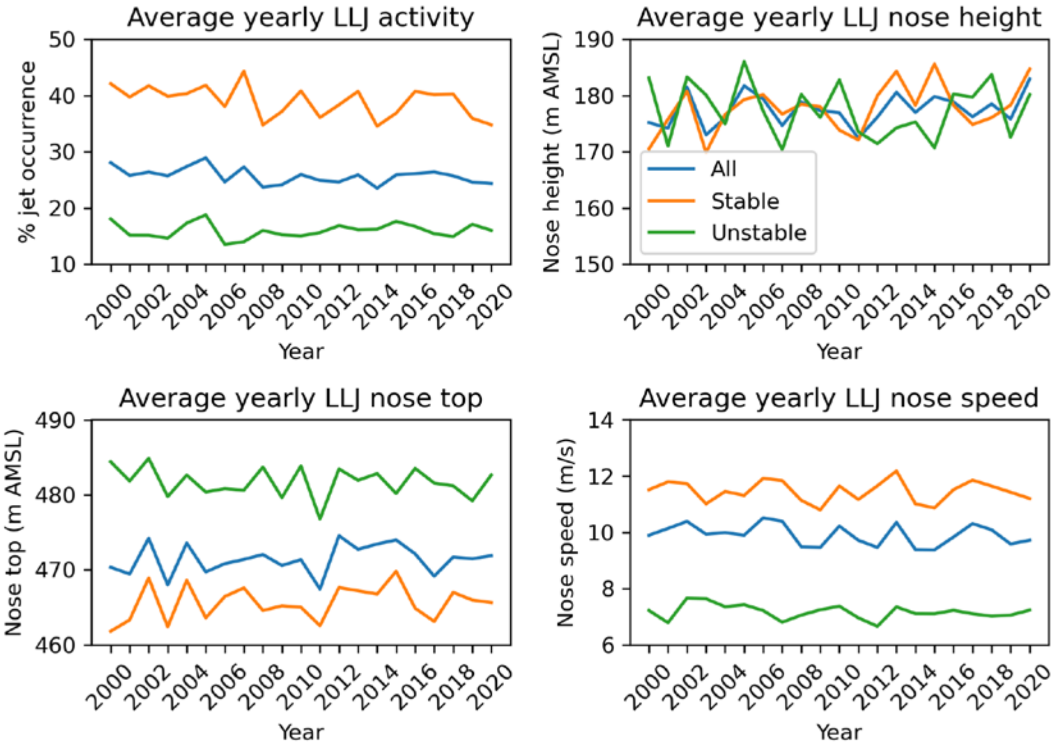
Intra-annual Variability Overshadows Interannual

- % jet occurrence:
  - Highest: 2005 (28.9%).
  - Lowest: 2014 (23.5%).
- LLJ nose heights:
  - Highest: 2020 (183 m).
  - Lowest: 2011 (172 m).
- LLJ nose tops:
  - Highest: 2012 (475 m).
  - Lowest: 2011 (467 m).
- LLJ nose speed:
  - Highest: 2006 (10.5 m/s).
  - Lowest: 2015 (9.38 m/s).



Interannual Stability Differences More Nuanced

- % jet occurrence:
  – Downward trend? Significance TBD.
- LLJ nose heights:
  – High interannual variability, but confined to 15–20 m.
- LLJ nose tops:
  – Low interannual variability.
- LLJ nose speeds:
  – Nose speeds are much slower in unstable conditions.

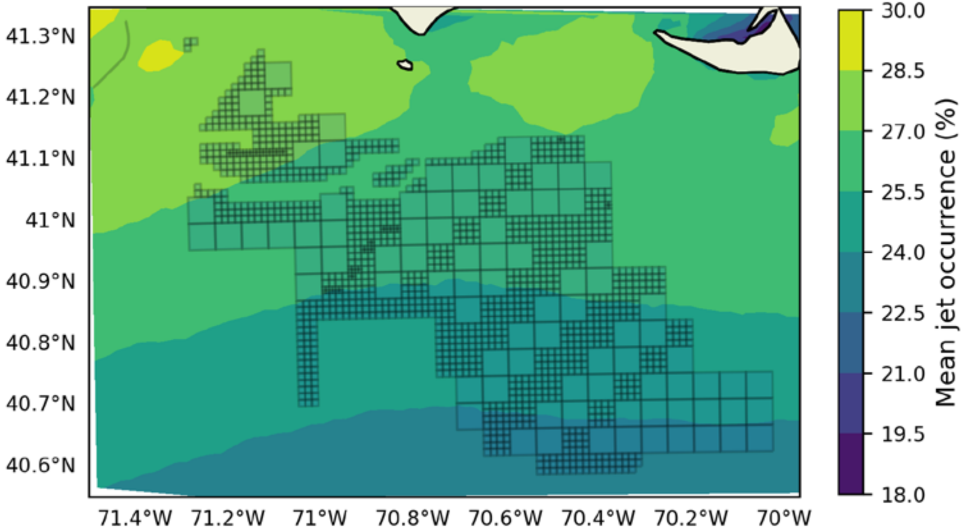


Wrap Up

Final thoughts, conclusions, and next steps

LLJs in the Rhode Island-Mass. Region Are Dynamic

- LLJs tend to have greater temporal variability than spatial variability.
- Stability makes a drastic difference in LLJ activity.
  - LLJs are over twice as likely to occur in stable conditions.
  - LLJs are spatially more variable in unstable conditions.
- LLJs are most variable temporally over the intra-annual cycle.
  - High seasonality, lower diurnal/interannual variability.
- Other variables such as wind direction and boundary layer height will be investigated next.



References

Debnath, M., P. Doubrawa, M. Optis, P. Hawbecker, and N. Bodini. 2021. "Extreme Wind Shear Events in US Offshore Wind Energy Areas and the Role of Induced Stratification." *Wind Energy Science* 6(4): 1043–1059. https://doi.org/10.5194/wes-6-1043-2021.

Kelley, N. D., B. J. Jonkman, and G. N. Scott. 2006. "The Great Plains Turbulence Environment: Its Origins, Impact, and Simulation" (Preprint). Golden, CO: National Renewable Energy Laboratory. NREL/CP-500-40176. https://www.nrel.gov/docs/fy07osti/40176.pdf.

Kelley, N., M. Shirazi, D. Jager, S. Wilde, J. Adams, M. Buhl, P. Sullivan, and E. Patton. 2004. *Lamar Low-Level Jet Project Interim Report*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-500-34593. https://www.nrel.gov/docs/fy04osti/34593.pdf.

Thank you!

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