Atmospheric Stability and Turbulence Characterization for Offshore Wind Turbines

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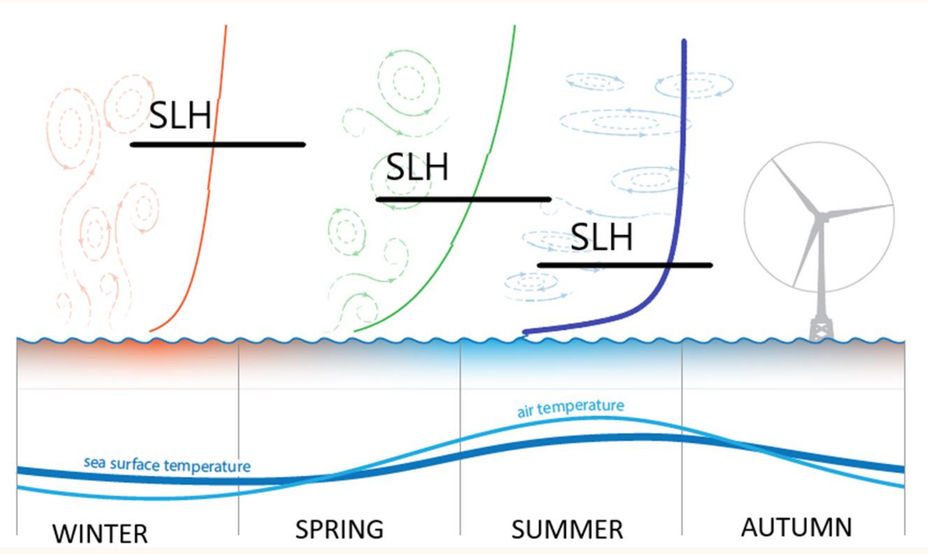
Validating NORA3 Reanalysis for Estimating Atmospheric Stability and Structure by Comparison with FINO-1 Observations



Introduction

The turbulent structure of the Atmospheric Boundary Layer (ABL) is highly dependent on atmospheric stability. With the latest generation of offshore wind turbines exceeding 250 meters in height, surface-based stability parameters, such as the Monin-Obukhov stability parameter, may not be sufficient to characterize the turbulent conditions at the height levels covered by the rotor disc.

However, observational data from offshore sites is scarce; even the largest meteorological towers only reach altitudes of around 100 meters. This lack of observational data motivates us to explore the ability of the 3km Norwegian Reanalysis (NORA3) to provide reliable stability estimates for the lower marine atmosphere.

In this study, we aim to validate the ability of the NORA3 reanalysis to estimate the stability and structure of the ABL by comparing the results to observations from FINO-1, a 101-meter mast situated in the German sector of the North Sea. This comparison will help us assess the performance of different stability parameters.

Objectives

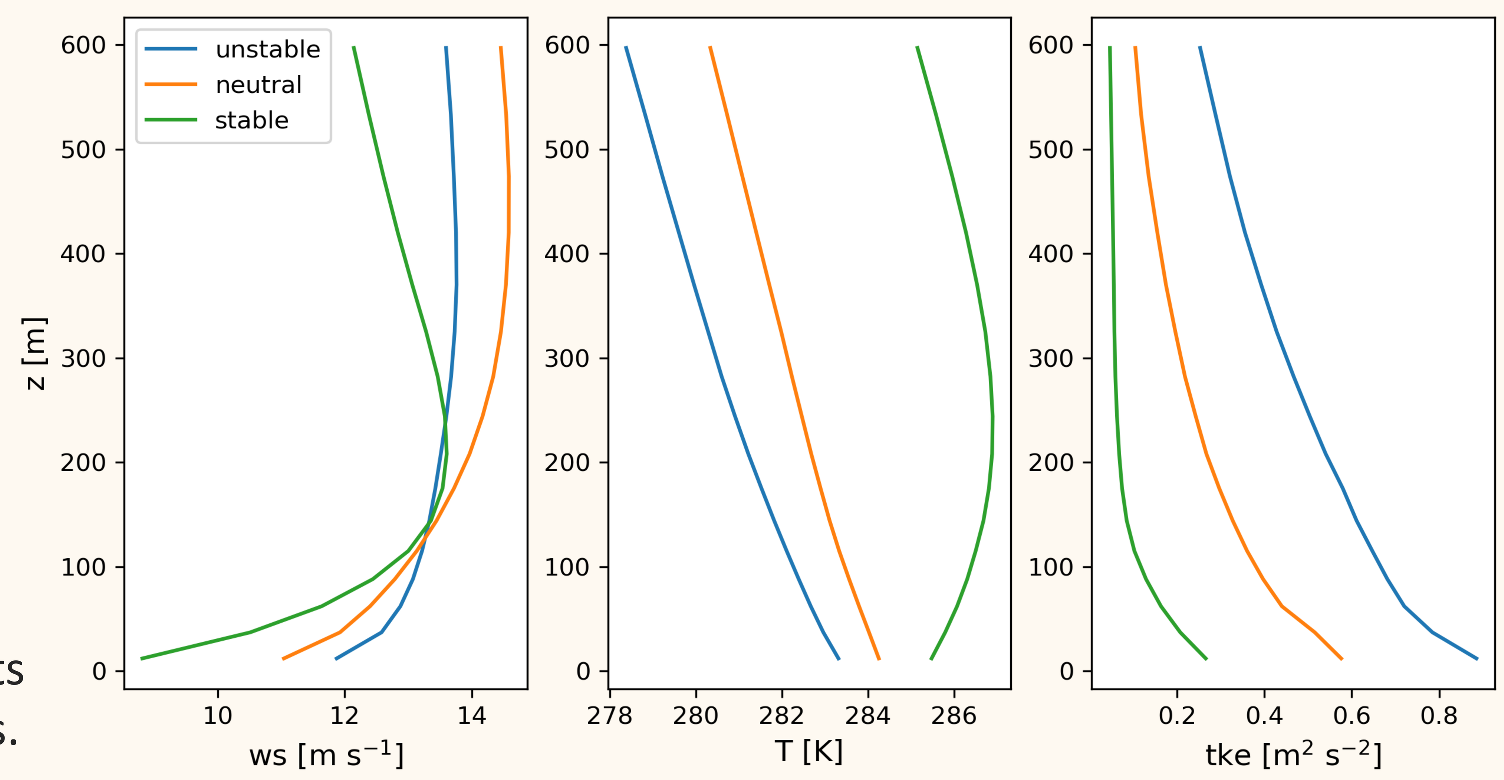
- **Main Goal**: To validate the ability of the NORA3 reanalysis to estimate the stability and structure of the Atmospheric Boundary Layer (ABL) for offshore wind applications.
- **Specific Objectives**:
  - Compare the performance of different stability parameters, including local and surface-based definitions of the Richardson number and the Monin-Obukhov stability parameter (z/L).
  - Assess the reliability of NORA3 stability estimates by comparing them to observational data from the FINO-1 mast.
  - Investigate the variation of turbulent fluxes and atmospheric stability with height, particularly in relation to the rotor disc heights of modern offshore wind turbines.

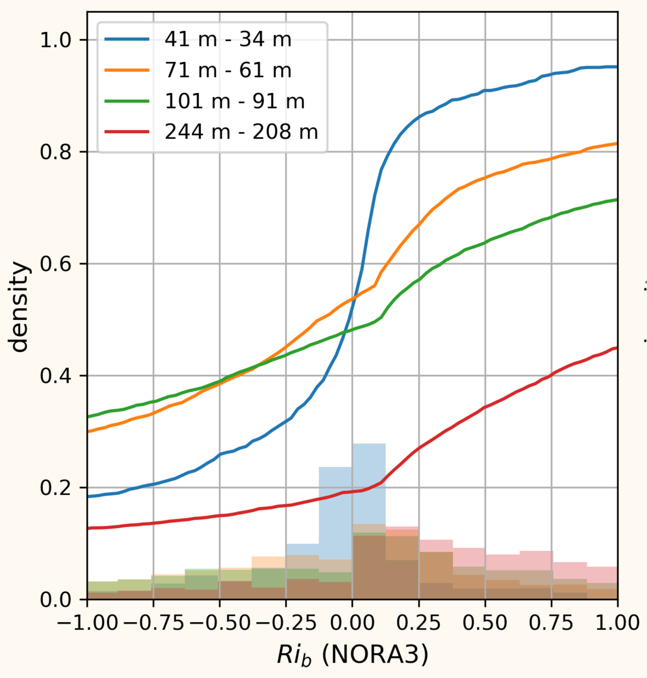
Methods

- **Data Sources**:
  - **NORA3 Reanalysis**: The 3km Norwegian Reanalysis (NORA3) is a high-resolution atmospheric dynamic downscaling of ERA5 (Haakenstad et al., 2021). NORA3 has been shown to be a valuable dataset for studies related to offshore wind applications (e.g., Solbrekke et al., 2021; Cheynet et al., 2024). Data output is available every 1 hour for important near-surface data at a relatively coarse height resolution, and every 3 hours for a broader selection of atmospheric parameters at a much denser height resolution (14 levels below 500 meters). Turbulent fluxes of momentum and heat are only available at the surface.
  - **FINO-1 Observational Data**: The FINO-1 mast is situated in the German sector of the North Sea, in proximity to the Alpha Ventus wind farm. It provides observational data at various heights, with three measurement levels equipped with sonic anemometers (41, 61, and 81 meters) and slow response temperature and wind observations at 34, 41, 51, 61, 81, 91, and 101 meters. This data is crucial for validating the stability estimates from NORA3, particularly for the study period from 2006 to 2009, before the commissioning of Alpha Ventus.
  - **Study Period**: The study focuses on the period from 2006 to 2009, before the commissioning of Alpha Ventus, to ensure undisturbed inflow conditions.
- **Stability Parameters**:
  - **Local and Surface-Based bulk Richardson number (Ri_b)** from neighboring height levels or with the surface as reference level using NORA3 and FINO-1 data.
  - **Inverse Obukhov length (1/L) and local Monin-Obukhov stability (z/L)** directly from sonic anemometer data (FINO-1), from NORA3 surface fluxes or employing a transfer function to Ri_b (Businger, et al., 1971).

Results

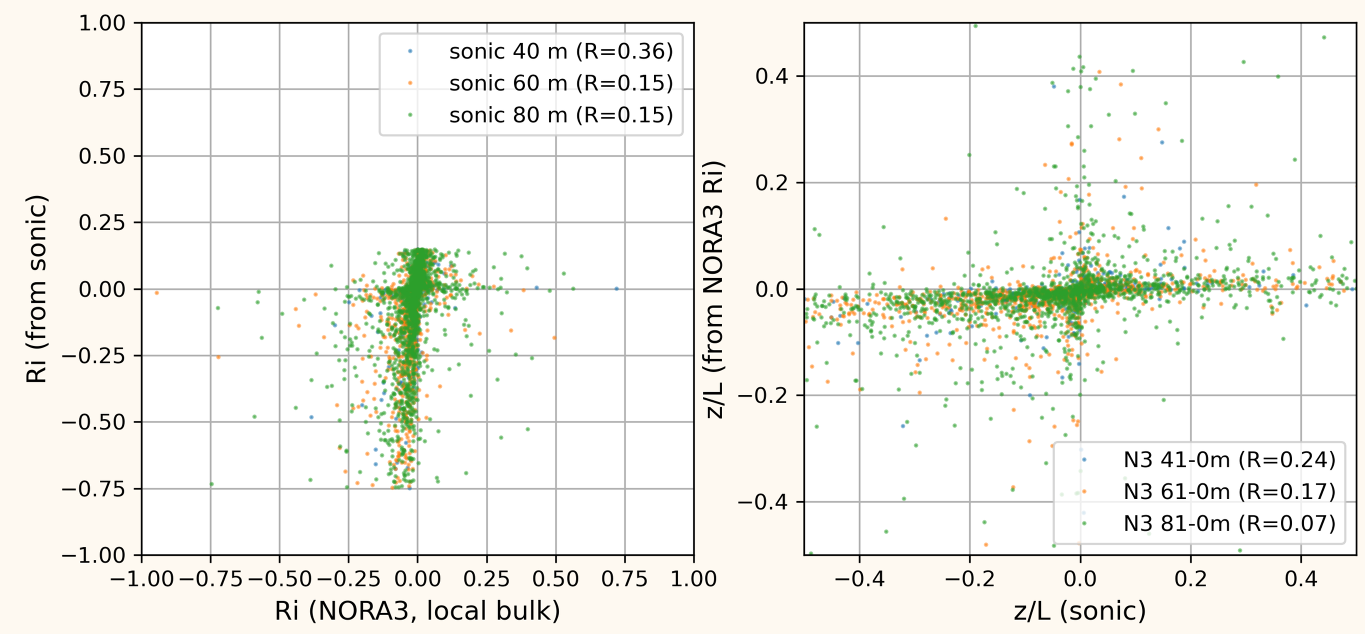
- **Mean Profiles Analysis for different stabiltiy classes:**
  - NORA3 produces distinct profiles of ws, T, and tke as a function of stability (for comparable wind speeds around hub-height), confirming the importance of atmospheric stability for offshore wind applications
    - **Stable:** Characterized by a mean Low-Level Jet (LLJ) and surface-based inversion, with weak tke close to the surface.
    - **Unstable:** Shows a sharper increase in wind speed near the surface, a stronger negative temperature gradient, and the highest levels of tke.
    - **Neutral:** Displays log-wind profile and intermediate tke-characteristics.

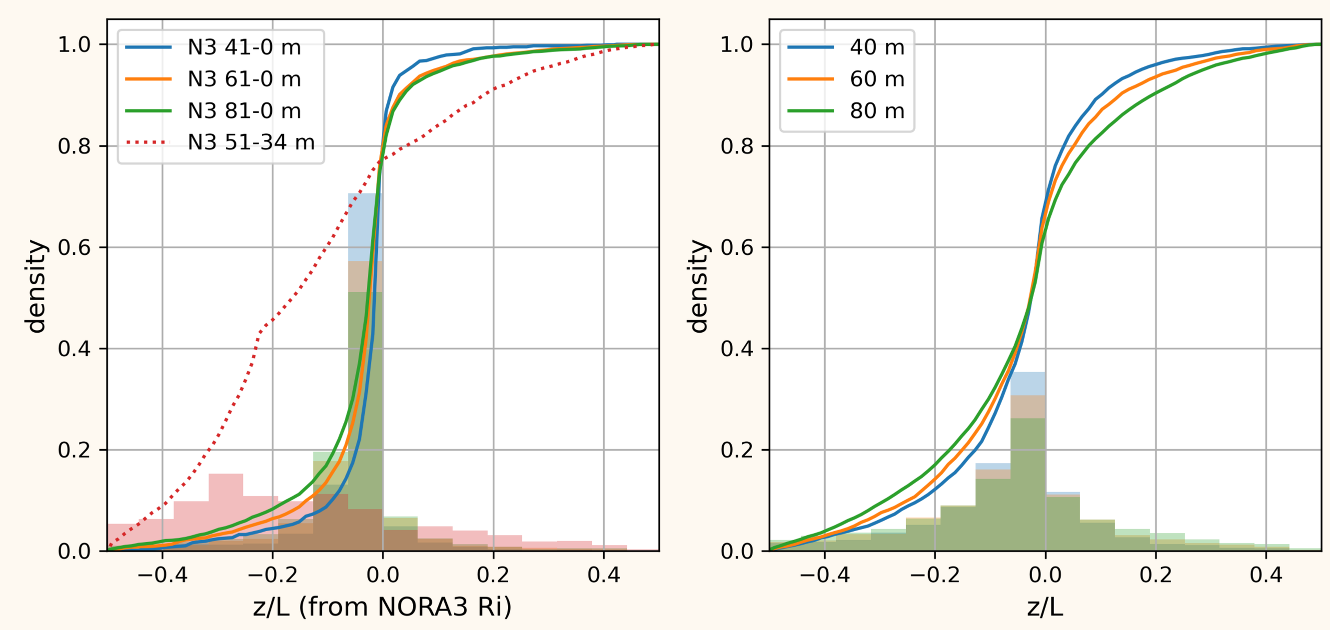


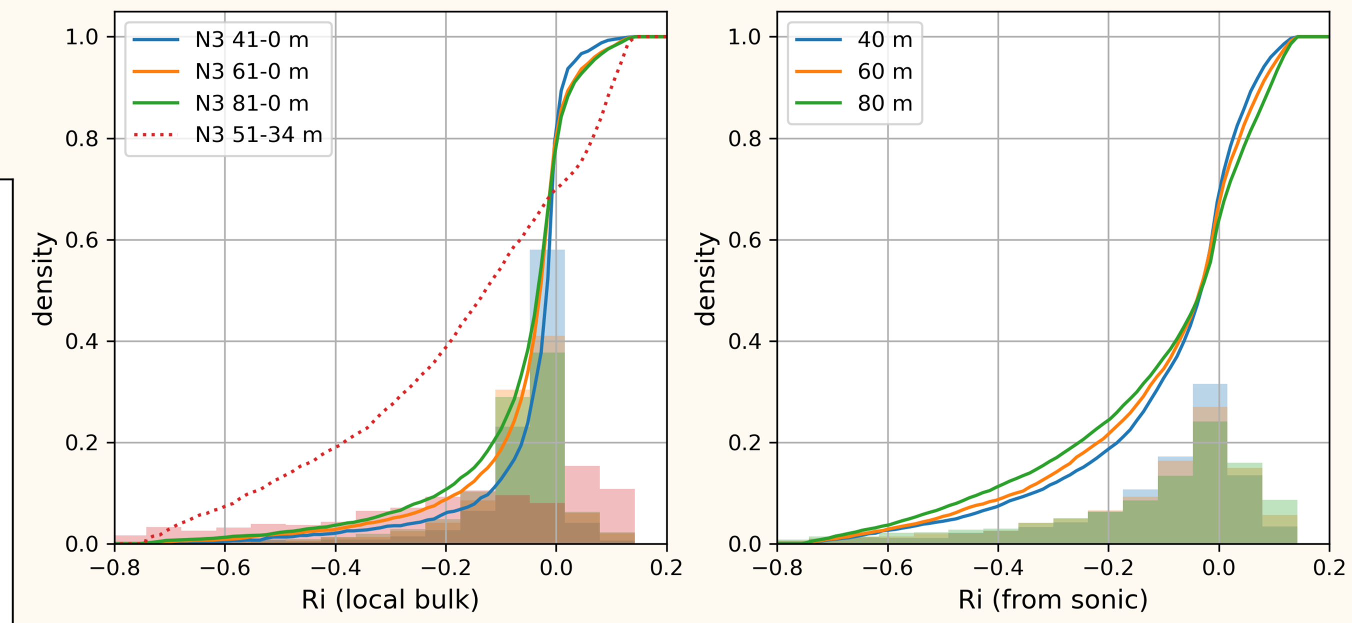


- **Change of Stability with Height**:
  Both NORA3 and observations show wider stability distributions at higher levels for different stability parameters (here surface-based Ri_b) with distinctly stronger stability at high levels.

- **Comparison Between Observation and NORA3-Based Stability:**
  - Comparison Between Observation and NORA3-Based Stability:
    - This comparison is complicated by two main factors:
      - NORA3 does not provide L or z/L at different heights
      - FINO-1 vertical temperature gradientsare subject to sensor drift and offsets, causing large uncertainties and inconsistencies in Ri_b
    - This requires a conversion function, which may also introduce uncertainty, particularly under very stable and unstable conditions.
- **Scatterplots:** The scatterplots show a general agreement but relatively weak correlation, which decreases with height.
- **Stability distributions** are generally similar, but observations show wider distributions.
- **Conversion Functions**: Converting observed z/L to Ri_b appears reasonable (not for local Ri_b), but conversion functions need to be adjusted to achieve more similar distributions.







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