CE669 (Atmospheric physics and chemistry) : Term Project

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A. Proposal for Meteorological Study Using the WRF Model

1. Model Description

The Weather Research and Forecasting (WRF) Model is a state-of-the-art, open-source mesoscale numerical weather prediction system designed for atmospheric research and operational forecasting.

WRF Framework

- **Dynamical cores**
  - **ARW**: fully compressible, non-hydrostatic; handles idealized cases, regional-climate, and coupled applications (chemistry, wind energy).
  - **NMM**: optimized for operational mesoscale forecasts.

- **Core features**: 3rd-order Runge–Kutta time stepping; high-order, scalar-conserving advection; full Coriolis/curvature/mapping; one- & two-way nesting with flexible lateral boundaries; comprehensive physics (microphysics, PBL, land-surface, radiation, cumulus); FDDA nudging; digital-filter initialization.

WRF Preprocessing System (WPS)

- Three sequential utilities, driven by **namelist.wps**:
  1. **geogrid**: sets domains, map projection, and interpolates static terrain/land-use.
  2. **ungrib**: extracts meteorological fields from GRIB1/2.
  3. **metgrid**: horizontally interpolates those fields onto the model grid.

2. Objective

- **Primary**: Characterize wind speed & direction over the proposed industrial area to guide stack placement, pollution dispersion, and wind-energy co-location.
- **Secondary**:
  - Assess seasonal and diurnal wind variability.
  - Provide validated high-resolution wind climatology for risk and safety planning.

3. Methodology

3.1 Working Principle

- **Nested, regional simulations**: parent domain (coarse) supplies boundary data to finer child nests down to ~1 km resolution.
- **Governing equations**: compressible Navier–Stokes in η-coordinates, with full treatment of advection, pressure gradients, Coriolis, buoyancy, diffusion, and terrain effects.
- **Data assimilation (optional)**: grid- or observation-nudging via FDDA to incorporate local measurements.

System prerequisites

- UNIX-like OS (Linux/macOS), `tcsh` or `bash` shell.
- Fortran compiler (gfortran ≥ 4.4.0, Intel, or PGI), C compiler (`gcc`), and `cpp`.
- Scripting languages: `csh`, `perl`, `sh`; UNIX tools: `make`, `grep`, `tar`, etc.

3.2 Installation & Environment Setup

1. **Core utilities** (STEP 01):
    - Shell: `csh`/`bash`; compilers: `gfortran` (≥ 4.4.0), `gcc`, `cpp`; tools: `make`, `tar`, `grep`, `perl`, etc.
2. **System tests** (STEP 02):
    - Verify `which gfortran`, `which gcc`, `which cpp`; run small Fortran and C test programs to confirm compiler compatibility.
3. **Library builds** (STEP 03–04):
    - Download & compile with same compilers:
        - **MPICH2**, **NetCDF** (v3/4), **zlib**, **libpng**, **JasPer**.
    - Run NetCDF+MPI integration tests to ensure I/O compatibility.
4. **WRF & WPS compilation** (STEP 05):
    - Unpack source into `WRFV3/` and `WPS/`.
    - In `WRFV3/`: `./configure` → select compiler/platform → `./compile em_real >& log.compile`.
    - In `WPS/`: `./configure` → `./compile >& log.compile`.
5. **Static geography data** (STEP 06):
    - Download `geog.tar.gz` (~15 GB) for terrain, land use, soil; unpack under `WPS/geo_data/`.
6. **Accessories** (STEP 07):
    - Install NCL or Python (`wrf-python`), ARWpost, GrADS for post-processing.

Sources: for **Installation & Environment Setup** [Youtube video WRF-ARW Complete Installation](), **Class slides.**

3.3 Domain & Parameter Setup

1. **`namelist.wps`** (geogrid/ungrib/metgrid):
    - Define nests (`parent_id`, `grid_ratio`, start indices), resolution (`dx`, `dy`), map projection (Lambert, etc.), and pointing to GRIB inputs & Vtable.

2. `namelist.input` (real+wrf): key sections:

    - **&domains**: `e_we`, `e_sn`, `e_vert`; `dx`/`dy`; `max_dom`; vertical levels.
    - **&time_control**: start/end dates; `interval_seconds` for boundary updates (6 h = 21600 s).
    - **&dynamics**: `non_hydrostatic=.true.`, diffusion/damping options.
    - **&physics**: select schemes (e.g. microphysics = WSM6, PBL = MYNN2, radiation = RRTMG) appropriate for wind studies.
    - **&bdy_control**: boundary widths, nesting flags.

3.4 Model Execution

1. **Preprocessing:**
    - In your WPS directory, run
      `./geogrid.exe` → `geo_em.d0*.nc`
      `./ungrib.exe` → `FILE:date`
      `./metgrid.exe` → `met_em.d0*.date.nc`
2. **Initialization:**
    - In `WRFV3/run`, execute
      `./real.exe` → `wrfinput_d0*`, `wrfbdy_d0*`
3. **Integration:**
    - Launch the model in parallel, e.g.
      `mpirun -np N ./wrf.exe` → `wrfout_d0*.<timestamp>.nc` + logs
4. **Nested domains:**
    - For one-way nests, after the parent run use
      `./ndown.exe` to generate child boundary inputs.

3.5 Data Post-Processing

- **ARWpost + GrADS:** convert NetCDF to GrADS control files; plot wind vectors, cross-sections.
- **Python (wrf-python):** extract 10 m winds (`uvmet10`), compute wind roses, diurnal cycles, summary stats.
- **NCL:** contour maps of wind speed and wind-power density.

4. Model Validation Procedures

- **Observational datasets**:
    - Surface stations (hourly wind speed & direction).
    - Supplement with reanalysis (ERA5/MERRA-2) for spatial context.

- **Verification metrics**:

Metric	Formula	Target
RMSE	$\sqrt{\frac{1}{N}\sum_{i=1}^{N}(M_i - O_i)^2}$	< 2 m/s
MAE	$\frac{1}{N}\sum_{i=1}^{N}\lvert M_i - O_i\rvert$	< 1 m/s
Correlation (r)	$r = \frac{\sum_{i=1}^{N}(M_i - \overline{M})(O_i - \overline{O})}{\sqrt{\sum_{i=1}^{N}(M_i - \overline{M})^2}\sqrt{\sum_{i=1}^{N}(O_i - \overline{O})^2}}$	> 0.8
Mean Bias (MB)	$\frac{1}{N}\sum_{i=1}^{N}(M_i - O_i)$	± 0.5 m/s
Normalized MSE	$\frac{\frac{1}{N}\sum_{i=1}^{N}(M_i - O_i)^2}{\overline{M}\,\overline{O}}$	< 1.5

- **Validation steps**:
    - **Temporal**: time-series scatter and bias analysis at each station.
    - **Spatial**: domain-wide wind error maps, Taylor diagrams.
    - **Directional**: compare modeled vs. observed wind-rose distributions.
    - **Sensitivity**: perturb physics schemes (PBL, microphysics) to minimize errors.

This structured approach leverages the robust WRF-ARW system and best practices for installation, configuration, execution, and validation to deliver reliable wind-field guidance for your industrial planning.

B.(i) Validation of WRF data (only for wind speed) against observed data

Use the python code(colab notebook link given in the references)
Reads my Excel file (`wind_data.xlsx`)
Extracts

- Cp = WRF-modelled wind speed (`WS10m`)
- Co = observed wind speed (`WSo`)

Implements **exactly** the formulas from PDF's Table 1, Prints out each statistic

Results:

Slope (β_1): 0.3774
Intercept (β_0): -0.0487
Fractional Bias (FB): -0.9537
NMSE: 3.1838
Pearson r: 0.4637
Index of Agrmnt (d): 0.4866

1. Slope (β_1 ≃ (value)): the ratio of variability in the modelled speed to that in the observations.

- **Ideal**: 1.0

Result: 0.38 ≪ 1 → the model **underestimates** the amplitude of fluctuations (peaks too low, troughs too high).

2. Intercept (β_0 ≃ (value) m/s) : a constant offset between model and observations. **Ideal**: 0

Result: 0.05 m/s → a negligible negative offset; at zero observed winds the model is ≈0.05 m/s lower.

3. Fractional Bias (FB ≃ (value)): Range: (–2, +2), ideal = 0

- **FB ≈ 0** → negligible mean bias.

FB > 0 → $\overline{C_o} > \overline{C_p}$, The model **underestimates** the mean wind speed.

FB < 0 → $\overline{C_o} < \overline{C_p}$, The model **overestimates** the mean wind speed.

Result: –0.95 → large **negative** bias means $\bar{C}_p > \bar{C}_o$; the model's **mean** wind speed is ~95 % higher than observed.

4. Normalized Mean Square Error (NMSE ≃ (value)) Ideal: 0

- Measures average squared error normalized by magnitudes; values below 0.5 indicate good model performance.

Result: 3.18 (≫ 0.5) →the squared errors are large relative to the magnitudes.

5. Pearson correlation (r ≃ (value)), Range: –1 to +1, ideal = +1

Values close to 1 signify strong alignment in timing and amplitude; r > 0.8 is typically "strong" for meteorological data.

Result: ~0.46 → weak to moderate correlation; the timing of peaks/troughs is modestly captured.

6. Index of agreement (d ≃ (value)), Range: 0 to 1, ideal = 1

Result: 0.49 (< 0.5) → poor overall agreement in both magnitude and phase.

Overall Model Validation

All but the intercept point to **poor performance**. WRF systematically **overestimates** mean winds (FB, MBE), **underrepresents** variability (slope ≪ 1), and shows only **weak temporal agreement** (r ~ 0.46, d < 0.5). The high NMSE confirms large normalized errors. We may need to revisit model physics, boundary conditions or post-processing filters to improve fit.

B (ii). Plotting the wind-rose:

1. **Get WRPLOT**
   – Download and install the wind-rose plotting tool from the WRPLOT website.

2. **Import your Excel data**
   – Open WRPLOT, go to **Tools** → **Import Data**, and select your WRF Excel file (with `Hour`, `WS10m`/`WSo`, `WD10m`/`WDo`).

3. **Map the data fields**
   – In the **Data Fields** tab, set:

• **Time unit** → `Hour` (0–23)
• **Wind speed** → `WS10m` (m/s) or `WSo`
• **Wind direction** → `WD10m` (°) or `WDo`

4. **Enter station info**
   – In **Station Information**, fill in:
   • **Station ID:** 1234
   • **Location:** Kanpur, UP (26.4499° N, 80.3319° E)
   • **Time zone:** UTC+5

5. **Generate the .sam file**
   – Click **Import**. WRPLOT will export a `.sam` file (viewable in WordPad).

6. **Load the .sam and plot**
   – Back on the Home screen, choose **Add File**, select your new `.sam`, and then open:
   • **Wind-rose diagram**
   • **Frequency count & distribution** (exports as CSV)

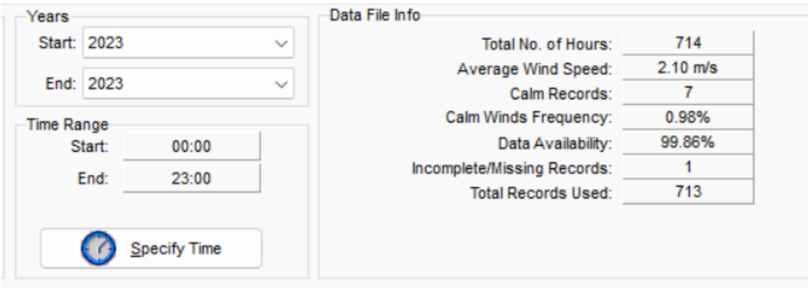

Figure 1 : November 2023 WRF Wind Data Summary (713 hr, 99.86 % Availability)

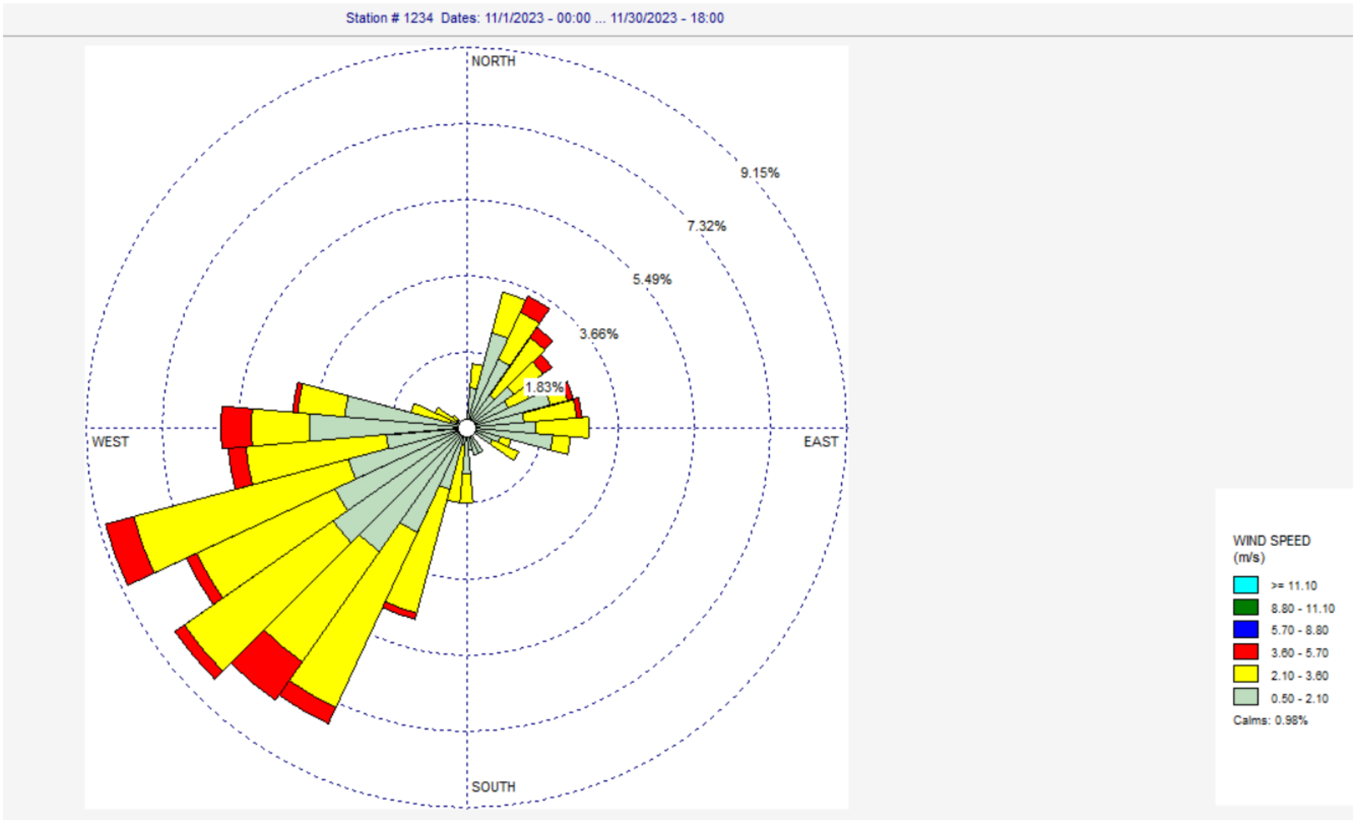

Figure 2 : November 2023 WRF Wind-Rose at Station #1234 (713 hr Data)

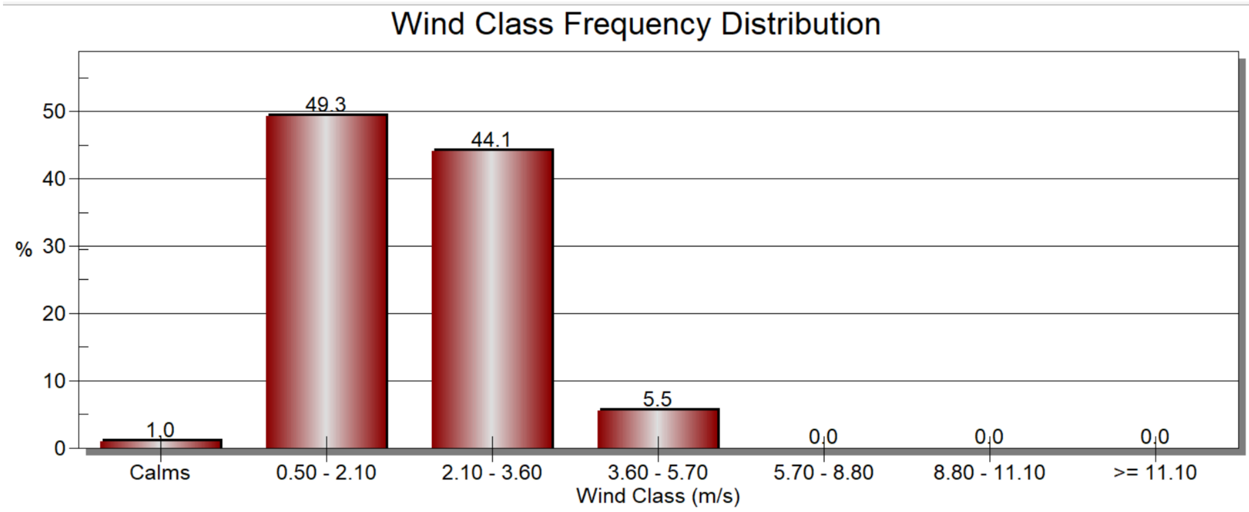

Figure 3 : Wind Speed Class Frequency (%) — November 2023 (WRF Data)

B(iii). Interpretation of Wind rose plot:

Over the 713 hours of WRF data (99.86 % complete) from 1 Nov to 30 Nov 2023, the wind-rose shows a clear, single-lobe pattern:

- **Dominant wind sector**: Winds blow most often from the **west–southwest (WSW)** quadrant (around 230°–260°).
- **Speed distribution**:
  - 49.3 % of the time at 0.5–2.1 m/s
  - 44.1 % at 2.1–3.6 m/s
  - Only 5.5 % at 3.6–5.7 m/s (and almost none above that)
- **Calms**: a mere 0.98 % of observations

Because the air almost always arrives at the site from WSW, any stack emissions will be carried **toward the east–northeast (ENE)**. To minimize the footprint of industrial pollutants on city residents, you should locate new facilities **on the ENE side of the city center**—that way the prevailing WSW breezes sweep emissions away from the urban core rather than into it.

Conclusion:

In sum, the WRF-based study delivered a clear wind-field assessment—highlighting systematic biases and timing mismatches—while the wind-rose revealed a dominant WSW flow. Placing new industrial sites ENE of the city center will ensure emissions are carried away from the urban core. Continued tuning of model physics and boundary settings is recommended to sharpen forecast accuracy.

References and data: below link consists all result files Drive link