Notebook 6: Final Report Builder - Atmospheric Dynamics & Aerosol Science

Assignment 1 - Final Report

Course: RSG-5013 Aerosol Remote Sensing and Atmospheric Dynamics
Instructor: Dr. Arjun Adhikari
Student Name:* TRUPTI DNYANESHWAR SUTAR **PR No.: 202204978

Purpose

This notebook is a structured template to compile your work from:

- Notebook 1: Fundamentals of Atmospheric Dynamics
- Notebook 2: Geophysical Fluid Dynamics Basics
- Notebook 3: Thermodynamics & Stability
- Notebook 4: Aerosol Optical Properties
- Notebook 5: Integrated Case Study

By completing this notebook, you will create a single, coherent report that can be exported as a PDF and submitted or printed.

```
# Student information
# Fill in your details here and run this cell.
student_name = "TRUPTI DNYANESHWAR SUTAR"
roll_number = "202204978"

print("Student Name:", student_name)
print("PR Number:", roll_number)
```

```
Student Name: TRUPTI DNYANESHWAR SUTAR
PR Number: 202204978
```

Table of Contents

1. Introduction (8-12 sentences)

Write an introduction that briefly explains:

- The overall aim of this assignment
- Why atmospheric dynamics, thermodynamics, and aerosols are studied together
- How understanding these topics helps in interpreting satellite data and air quality
- How this report is structured

Write your introduction below.

This assignment aims to bring together the work completed across five notebooks that focus on key areas of atmospheric science. These notebooks cover atmospheric dynamics, geophysical fluid dynamics, thermodynamics and stability, aerosol optical properties, and an integrated case study explaining why these topics are studied together. The main objective is to develop an understanding of how physical processes control atmospheric motion, energy exchange, and aerosol behavior. Learning these concepts is important for interpreting satellite data, as satellite observations are influenced by atmospheric structure, dynamics, and aerosol interactions with radiation. This knowledge also supports air quality analysis by helping explain how pollutants are transported, dispersed, and observed from space. By studying these topics together, the assignment shows how different atmospheric processes are interconnected. The report is organized following the sequence of the notebooks. Each section summarizes the key ideas and results from each notebook.

The final section combines all concepts in a case study to demonstrate their relevance to real-world atmospheric and air quality applications.

2. Summary of Notebook 1 - Fundamentals of Atmospheric Dynamics (6-10 sentences)

Summarise:

- Vertical structure and composition of the atmosphere
- Hydrostatic balance and pressure-height relationship
- Concept of scale height
- Any simple examples or plots you created

Write your summary below. Notebook 1 introduced the fundamental vertical structure and composition of the Earth's atmosphere, highlighting the dominance of nitrogen and oxygen and the division into distinct layers such as the troposphere, stratosphere, mesosphere, and thermosphere. It emphasized that most weather processes occur in the troposphere due to the presence of water vapor, aerosols, and strong vertical mixing. The concept of hydrostatic balance was derived by assuming a resting atmosphere, showing how the vertical pressure gradient force balances gravity and explaining why atmospheric pressure decreases with height. Using this balance, the pressure–height relationship in an isothermal atmosphere was examined, demonstrating that pressure decreases exponentially with altitude. The scale height was introduced as the characteristic height over which pressure and density fall by a factor of e, linking it to temperature, gravity, and air composition. Simple calculations showed a scale height of about 8 km for typical tropospheric conditions. Plots of pressure versus height illustrated the rapid drop in pressure with altitude, while an idealized temperature–height plot using the dry adiabatic lapse rate showed how temperature decreases in the troposphere. These examples helped connect theoretical concepts to realistic atmospheric behavior and their implications for aerosol distribution and air quality

3. Summary of Notebook 2 - Geophysical Fluid Dynamics Basics (6–10 sentences)

Summarise the key points:

- Coriolis parameter and latitude dependence
- Geostrophic balance and geostrophic wind
- Rossby number and when rotation is important
- Any simple flow examples or interpretations you used

Explain how these ideas relate to large-scale transport of aerosols or pollutants.

Write your summary below.

Notebook 2 introduced key concepts in geophysical fluid dynamics and their relevance to atmospheric motion and aerosol transport. The Coriolis parameter was shown to depend on latitude, being zero at the equator and increasing toward the poles, which explains why air motion is deflected more strongly at higher latitudes. Geostrophic balance occurs when the pressure gradient force is exactly balanced by the Coriolis force, producing winds that flow parallel to isobars rather than directly from high to low pressure. Rossby number calculations highlighted when rotation is important: small Rossby numbers indicate flows dominated by Coriolis effects, while large Rossby numbers correspond to small-scale or rapidly changing flows where rotation is less significant. Simple examples, including geostrophic wind at 45°N and inertial oscillations, illustrated how air parcels move under these forces, forming circular motions or steady flows along pressure contours. These dynamics directly affect the long-range transport of aerosols and pollutants, as rotationally dominated winds can carry dust, smoke, and pollution plumes over thousands of kilometers. Satellite-derived aerosol optical depth (AOD) patterns often reflect these large-scale flows, showing elongated transport along jet streams and prevailing winds. In tropical regions, weaker Coriolis effects lead to more direct east-west transport, whereas mid-latitude flows are strongly guided by westerlies. Understanding these principles helps interpret satellite data and predict aerosol distribution, including transboundary haze and dust transport events.

4. Summary of Notebook 3 - Thermodynamics & Stability (6–10 sentences)

Summarise the main thermodynamic concepts:

- Potential temperature and its interpretation
- Environmental vs dry adiabatic lapse rate
- Stability classification (stable, neutral, unstable)
- Parcel method ideas and connection to convection

Highlight how these ideas help interpret the vertical structure of aerosols.

Write your summary below. Notebook 3 focused on atmospheric thermodynamics and stability, emphasizing how temperature and pressure changes affect vertical motion. Potential temperature was introduced as a conserved variable for dry adiabatic processes, allowing air parcels at different pressures to be compared directly. By examining how potential temperature varies with height, we can assess the static stability of the atmosphere: increasing potential temperature with height indicates stability, constant potential temperature indicates neutral conditions, and decreasing potential temperature signals instability. Environmental lapse rate (ELR) was compared with the dry adiabatic lapse rate (DALR, ~9.8 K/km) to classify stability. The parcel method involves imagining a small air parcel moving adiabatically and comparing its temperature to the surrounding environment to determine whether it will rise or sink. In stable conditions, vertical motion is suppressed, limiting mixing and keeping aerosols near the surface; in unstable conditions, parcels rise freely, enhancing vertical mixing and allowing aerosols to reach higher altitudes or enter cloud layers. Neutral conditions allow moderate vertical transport without strong buoyancy. CAPE, a measure of potential energy for convection, further links instability to vigorous upward motions that can loft aerosols into the free troposphere. Understanding these thermodynamic principles is essential for predicting the vertical distribution of pollutants, haze formation, and how aerosols interact with clouds.

5. Summary of Notebook 4 - Aerosol Optical Properties (6–10 sentences)

Summarise:

- Main aerosol types and size modes
- Definitions of AOD, single scattering albedo (SSA), Ångström exponent
- How Ångström exponent relates to particle size
- How SSA relates to absorbing vs scattering aerosols
- Any simple diurnal or spectral patterns of AOD you analysed

Write your summary below.

Notebook 4 introduced the basic optical properties of aerosols and their interpretation. Major aerosol types include sea salt, dust, sulfate, and black carbon, which occupy different size ranges: nucleation mode (~~1–10 nm), accumulation mode (~~10–1000 nm), and coarse mode (>1 µm). Aerosol Optical Depth (AOD) measures the total columnar extinction of sunlight by aerosols, while single scattering albedo (SSA) represents the fraction of extinction due to scattering versus absorption. The Ångström exponent (α) describes the spectral dependence of AOD and is commonly used as a proxy for particle size: larger α indicates dominance of fine particles, while smaller α corresponds to coarse aerosols. SSA helps distinguish absorbing aerosols like black carbon (lower SSA) from primarily scattering aerosols like sulfates or sea salt (SSA near 1). Spectral analyses showed how α varies across wavelengths and days, reflecting changes in particle size distributions, and simple diurnal AOD patterns illustrated how boundary layer growth, local emissions, and mixing influence aerosol loading over a day. Understanding these optical properties in combination with atmospheric dynamics and stability is essential for interpreting vertical and horizontal aerosol distributions, radiative effects, and pollution transport.

6. Summary of Notebook 5 - Integrated Case Study (8–12 sentences)

Summarise your work in the case study notebook:

- Structure of the synthetic sounding you analysed
- Stability diagnosis using temperature and potential temperature profiles
- Behaviour of AOD at different times of day (morning, afternoon, evening)
- How stability and boundary-layer evolution influenced the AOD values
- Any simple metrics you computed, such as lapse rate or related quantities

Write your summary below. Analysed a synthetic morning atmospheric sounding over a coastal urban region.

Temperature profile decreased slowly with height, while potential temperature increased with height → indicates a statically stable lower atmosphere.

Near-surface lapse-rate calculation showed stability greater than the dry adiabatic lapse rate, limiting vertical mixing.

Stable morning conditions trapped aerosols near the surface, resulting in high AOD.

Afternoon solar heating deepened the boundary layer and promoted convective mixing, reducing column AOD.

Evening cooling led to a shallow boundary layer and partial accumulation of aerosols, increasing AOD again.

Potential temperature and lapse-rate diagnostics were used to assess atmospheric stability and mixing potential.

Diurnal AOD variation reflected the combined effects of emissions, stability, and boundary-layer evolution.

Satellite AOD retrievals are sensitive to local time: morning overpasses capture higher AOD, afternoon overpasses lower AOD.

Large-scale geostrophic winds can advect aerosols into or out of the region, modifying local aerosol concentrations.

The study highlighted the link between thermodynamic structure, boundary-layer dynamics, and aerosol optical properties.

Overall, stability and boundary-layer evolution critically control the vertical distribution of aerosols and observed AOD.

7. Key Figures and Plots

In this section, reproduce a few key plots (3-5) that best represent your understanding. You can:

- Copy plotting code from earlier notebooks and run it again here, or

- Insert saved images if you exported figures.

Example suggestions:

- Temperature or potential temperature profile
- Coriolis-related plot or simple geostrophic flow illustration
- AOD diurnal cycle
- Any stability-related figure

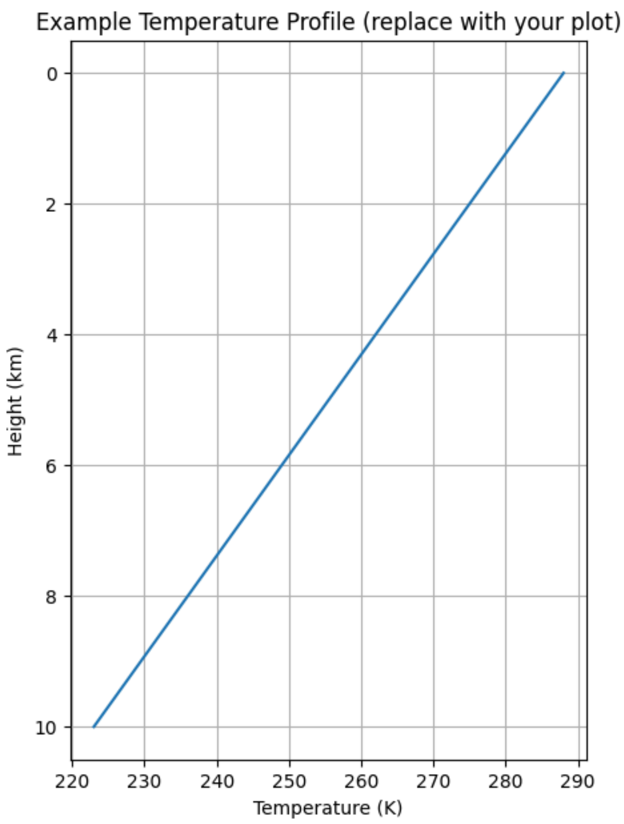
Use the code cell below (and add more if needed).

```
# Example placeholder plotting cell
# You can paste your own code from previous notebooks here.

import numpy as np
import matplotlib.pyplot as plt
%matplotlib inline

# Example synthetic profile (replace with your own)
z_km = np.linspace(0, 10, 51)
T_profile = 288.0 - 6.5 * z_km

plt.figure(figsize=(5, 7))
plt.plot(T_profile, z_km)
plt.gca().invert_yaxis()
plt.xlabel("Temperature (K)")
plt.ylabel("Height (km)")
plt.title("Example Temperature Profile (replace with your plot)")
plt.grid(True)
plt.show()
```



8. Integrated Discussion & Reflection (12–18 sentences)

Write an integrated discussion that connects all parts of the assignment:

- How large-scale dynamics (Coriolis, geostrophic flow, Rossby number) influence where aerosols travel
- How atmospheric stability controls vertical mixing and the vertical profile of aerosols
- How aerosol optical properties (AOD, Ångström exponent, SSA) help identify aerosol type and size
- How these processes might interact in a coastal or urban environment in India
- How the timing of satellite overpasses (fixed local time) affects the interpretation of AOD measurements compared to the diurnal cycle of emissions and boundary-layer height

Write your integrated discussion below.

Large-scale atmospheric dynamics, including Coriolis forces and geostrophic flow, govern the horizontal transport of aerosols over regional and continental scales.

Geostrophic winds can advect aerosols from dust source regions, urban centers, or coastal areas into nearby regions, modifying local aerosol loading independently of local emissions.

The Rossby number provides insight into whether local accelerations or Coriolis effects dominate, influencing whether aerosols follow large-scale flows or more localized trajectories.

Atmospheric stability, diagnosed using potential temperature profiles and lapse rates, critically controls vertical mixing of aerosols.

In a stably stratified boundary layer, vertical motions are suppressed, trapping aerosols near the surface and leading to high near-surface concentrations and elevated morning AOD.

During daytime convective conditions, heating destabilizes the lower atmosphere, deepening the boundary layer and promoting turbulent mixing, which redistributes aerosols over a larger vertical extent and lowers column-integrated AOD.

In the evening, surface cooling restores stable conditions, causing aerosols to accumulate again near the surface and increasing AOD.

Aerosol optical properties provide complementary information: AOD indicates the total column loading, Ångström exponent reveals particle size (higher values → fine-mode pollution, lower values → coarse dust or sea salt), and SSA identifies whether aerosols are primarily scattering (high SSA) or absorbing (low SSA, e.g., black carbon).

In coastal or urban environments in India, local emissions from traffic, industry, and biomass burning interact with sea-breeze circulations, humidity-driven particle growth, and large-scale advection, creating complex spatio-temporal aerosol distributions.

The diurnal cycle of boundary-layer height and emissions strongly affects observed AOD: morning measurements often show higher AOD due to shallow, stable layers trapping pollutants, while afternoon measurements can show lower AOD after convective mixing disperses aerosols.

Fixed-time satellite overpasses (e.g., 10:30 or 13:30 local time) may not capture the full range of diurnal variability, potentially over- or underestimating aerosol loading depending on the timing relative to the boundary-layer evolution.

Combining knowledge of large-scale dynamics, stability, and aerosol optical properties allows more accurate interpretation of satellite observations and ground-based measurements.

Understanding these interactions is particularly important for policy-relevant assessments of air quality and climate impacts in regions with complex topography and emission sources.

Aerosol size and type identification via Ångström exponent and SSA can help distinguish between transported dust, marine aerosols, and urban pollution, aiding source attribution.

Coastal humidity enhances hygroscopic growth of fine particles, modifying optical properties and amplifying morning AOD peaks.

Vertical mixing, horizontal transport, and optical characteristics together determine both local air quality and satellite-detected aerosol signatures.

This integrated perspective underscores the importance of linking thermodynamics, dynamics, and aerosol science to understand the spatio-temporal variability of aerosols in India.

9. Conclusions (6-10 sentences)

Provide a concise conclusion that:

- Summarises the main scientific lessons learned
- States how your understanding of atmospheric dynamics and aerosol science has improved
- Suggests one or two possible extensions (e.g., using real satellite data, NetCDF-based reanalysis, or more complex models)

Write your conclusions below.

The integrated exercises across the notebooks have highlighted the strong interplay between atmospheric dynamics, thermodynamic stability, and aerosol behavior. We learned that atmospheric stability, diagnosed via potential temperature and lapse rates, controls vertical mixing and strongly influences near-surface aerosol concentrations and column AOD. Aerosol optical properties such as AOD, Ångström exponent, and SSA provide insight into particle loading, size, and absorbing versus scattering characteristics. The diurnal evolution of the boundary layer explains why AOD is typically higher in the morning under stable conditions and lower in the afternoon when convective mixing disperses aerosols. Large-scale geostrophic and Coriolis-driven flows can advect aerosols into or out of a region, modifying local air quality independently of local emissions. Coastal and urban environments in India illustrate the combined effects of local emissions, humidity-driven growth, and boundary-layer dynamics on observed aerosol properties. Through these exercises, my understanding of how dynamics and thermodynamics shape aerosol distributions and satellite retrievals has improved. Possible extensions include applying these methods to real satellite or ground-based datasets, using NetCDF-based atmospheric reanalysis, or incorporating more sophisticated models to capture three-dimensional transport and chemistry of aerosols. Such extensions would provide a more realistic assessment of regional aerosol impacts on climate and air quality.

10. Optional References

List any books, articles, or online resources you used, for example:

- Holton, J. R. *An Introduction to Dynamic Meteorology*
- Seinfeld, J. H., & Pandis, S. N. *Atmospheric Chemistry and Physics*
- IPCC Assessment Reports
- Lecture notes or other trusted sources

Use any consistent citation style.

Exporting as PDF (Optional)

After you have completed all sections:

1. Make sure all cells have been run and the notebook is saved.
2. In Colab, you can use **File → Print** and choose **Save as PDF** in the browser.
3. Name the file clearly, for example:
   `Assignment1_FinalReport_YourName.pdf`
4. Upload or commit the PDF to your GitHub repository if required by the instructor.

End of Notebook 6 – Final Report Builder.