Lecture 09. Topical Lidar Overview

- Introduction to topical lidars
- Why topical lidars?
- Temperature techniques
- Wind techniques
- Aerosol techniques
- Constituent techniques
- Target & altimeter techniques
- Summary

Introduction to Topical Lidars

- Topics we will discuss in this class are

1. Temperature (structure from ground to thermosphere, diurnal/seasonal/interannual variations, etc.)
2. Wind (structure from ground to upper atmosphere, its variations, etc.)
3. Aerosols and clouds (distribution, extinction, composition, size, shape, and variations spatially and temporally)
4. Constituents (O_3, CO_2, H_2O, O_2, N_2^+, He, metal atoms like Na, Fe, K, Ca, pollution, etc)
5. Target & altimetry (identification, accurate height & range determination, fish, vibration, etc.)

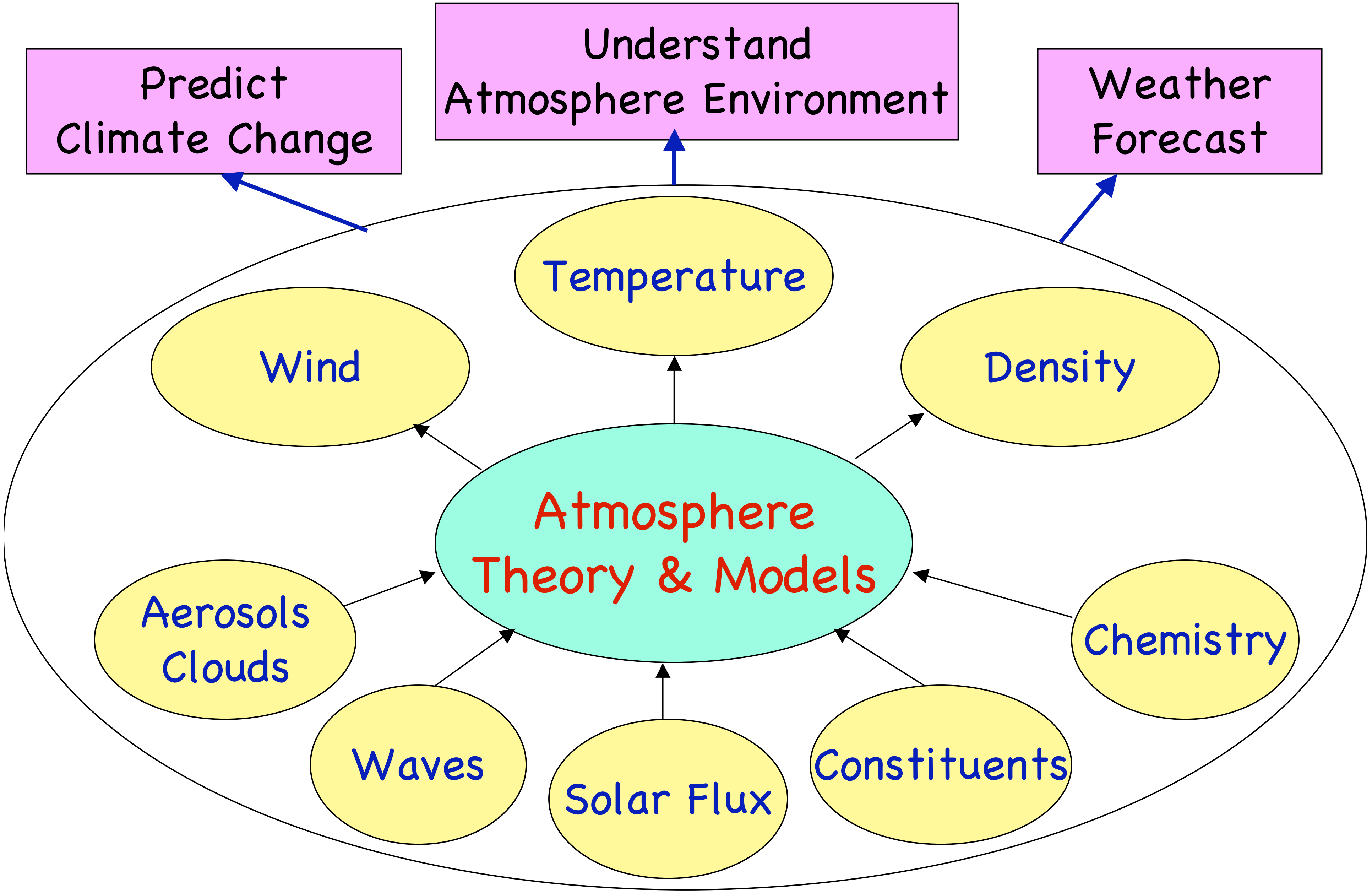
Why Topical Lidars ?

- To compare different lidar techniques that address the same topic, e.g., how many ways to measure temperature, and what's the essential point among these different lidars?
- To illustrate the strengths and limitations of each different type of lidars, and give an insight of when and where to use what kind of lidars?
- To encourage students to explore new phenomena or effects to invent novel lidars / methods.

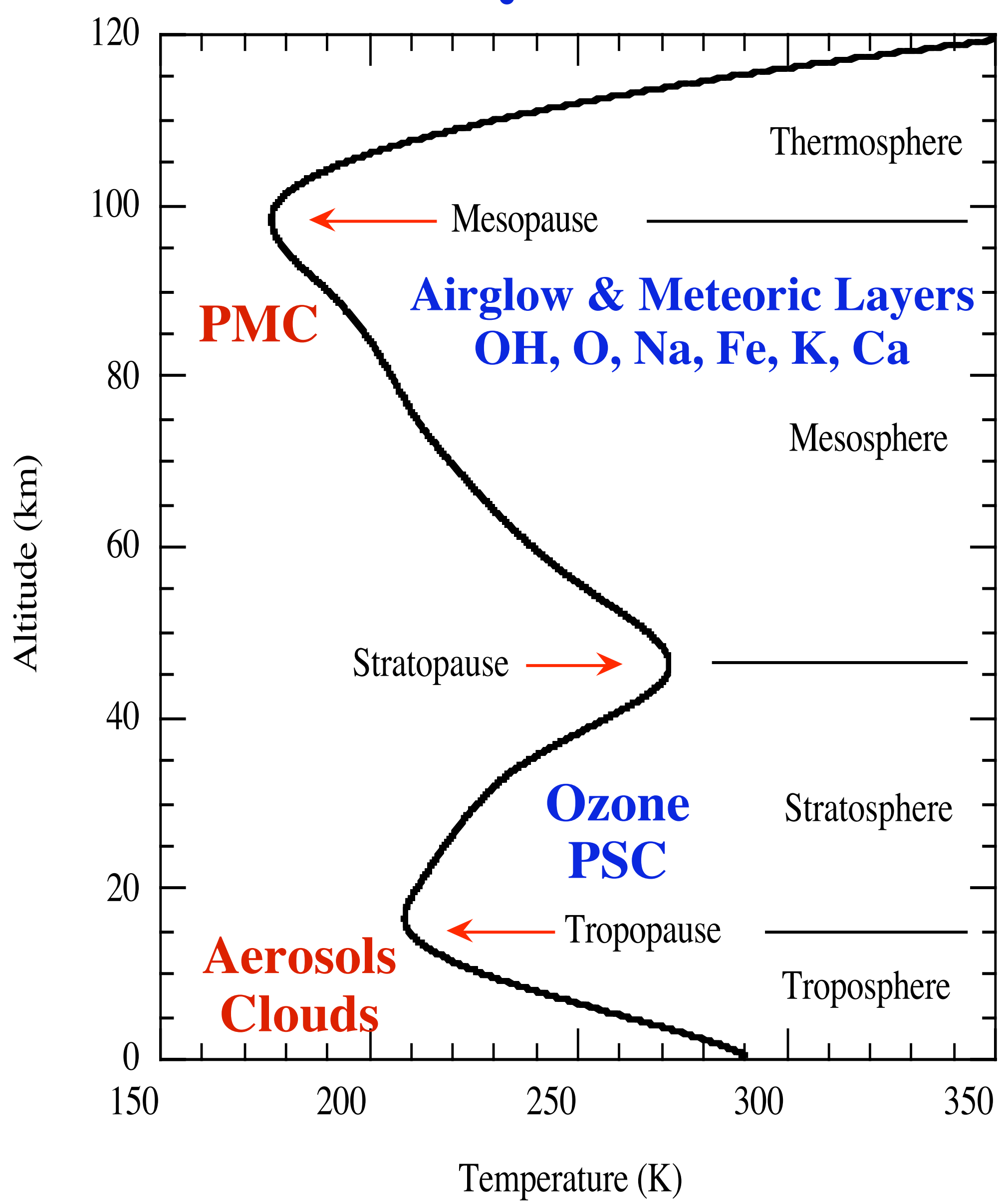
Why These Five Topics ?

- These are five most interesting and hot topics in the atmospheric/space science, environmental research, and climate study.
- They also have wide applications in environmental monitoring, national defense, and industry applications.
- The lidar technologies used to address these five topics represent the key technology advancement in the past 20 years.
- There are also high potentials of future advancement in these aspects, so encouraging creative students to pursue technology innovation, development, implementation, as well as applying the existing and future technology to conduct novel science/environmental research.

Observables in Atmos Models



Temperature Techniques

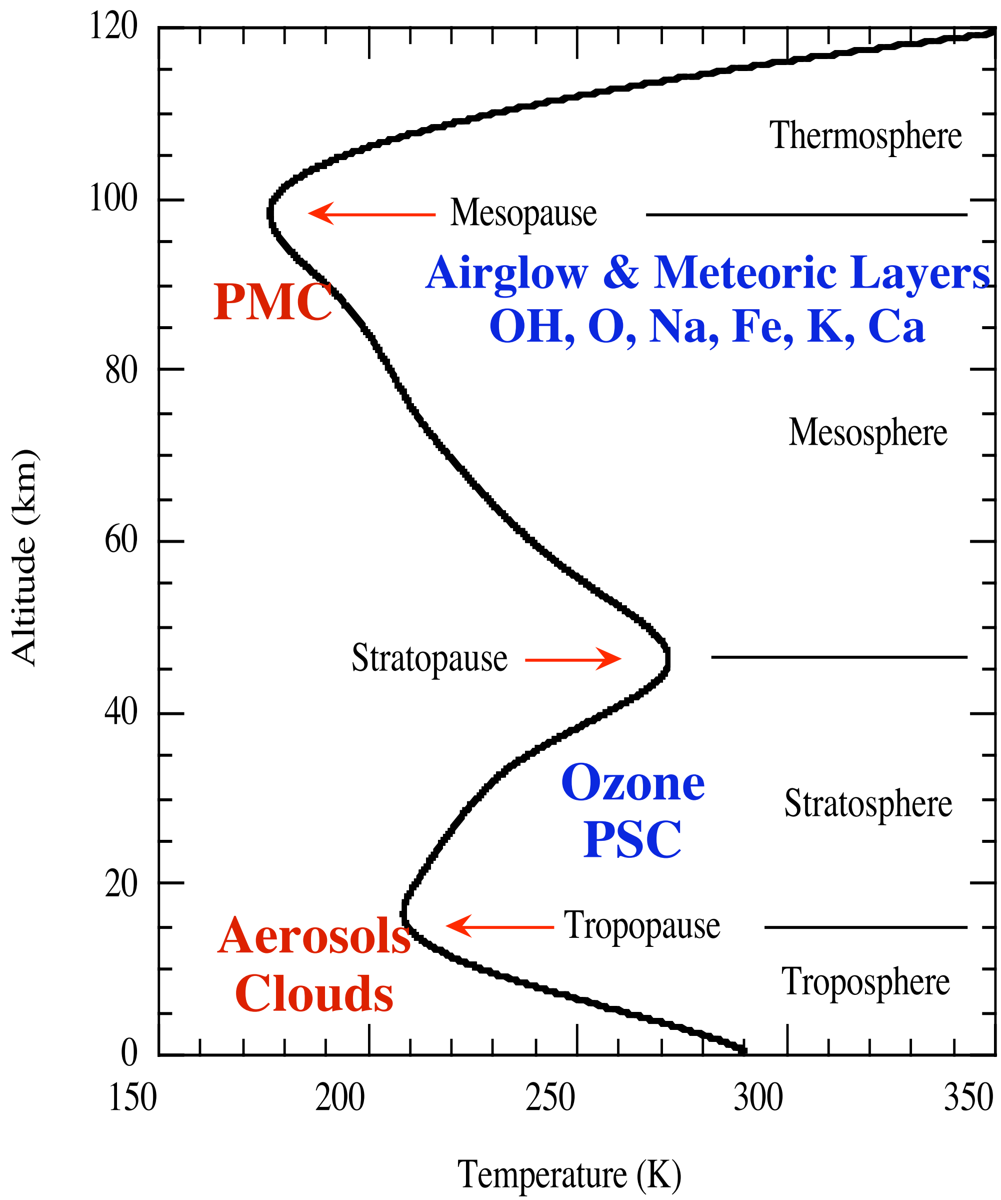


- ❑ 75-120km: resonance fluorescence Doppler technique (Na, K, Fe) & Boltzmann technique (Fe, OH, O_2)
- ❑ 30-90km: Rayleigh integration technique & Rayleigh Doppler technique
- ❑ Below 30 km: scattering Doppler technique and Raman technique (Boltzmann and integration)
- ❑ Boundary layer: DIAL, HSRL, Rotational Raman

Comparison of Temperature Technique

Technique	Lidars	Applications
Doppler Technique: temperature dependence of Doppler broadening (1 time Doppler shift and Doppler broadening for single absorption or emission process) (2 times Doppler shift and Doppler broadening for Rayleigh scattering)	Resonance fluorescence Doppler Lidar: Doppler broadening and Doppler shift of resonance fluorescence absorption cross-section (scan and ratio techs)	Mesosphere and Lower Thermosphere temperature and wind (75-120 km)
	Rayleigh Doppler Lidar : Doppler broadening of molecular scattering	Lower mesosphere, stratosphere and troposphere temperature and wind (up to 60 km)
	High-Spectral-Resolution Lidar: Doppler broadening of molecular scattering, ratio of two signals	Stratosphere and troposphere temperature and wind (up to 30 km)
Boltzmann Technique: temperature dependence of population ratio	Resonance fluorescence Boltzmann Temperature Lidar: population ratio on the lowest two ground states	Mesosphere and Lower Thermosphere temperature (75-120 km)
	Rotation Raman Temperature Lidar: ratio of two Raman line intensities and population on different initial energy states	Troposphere and stratosphere temperature
Integration Technique: hydrostatic equilibrium and ideal gas law	Rayleigh Integration Temperature Lidar: atmospheric density ratio to temperature, integration from upper level	Stratosphere and mesosphere temperature (30-90 km)
DIAL	Differential Absorption Lidar: Temp-dependence of line strength and lineshape	Boundary layer temperature

Wind Techniques vs Altitude



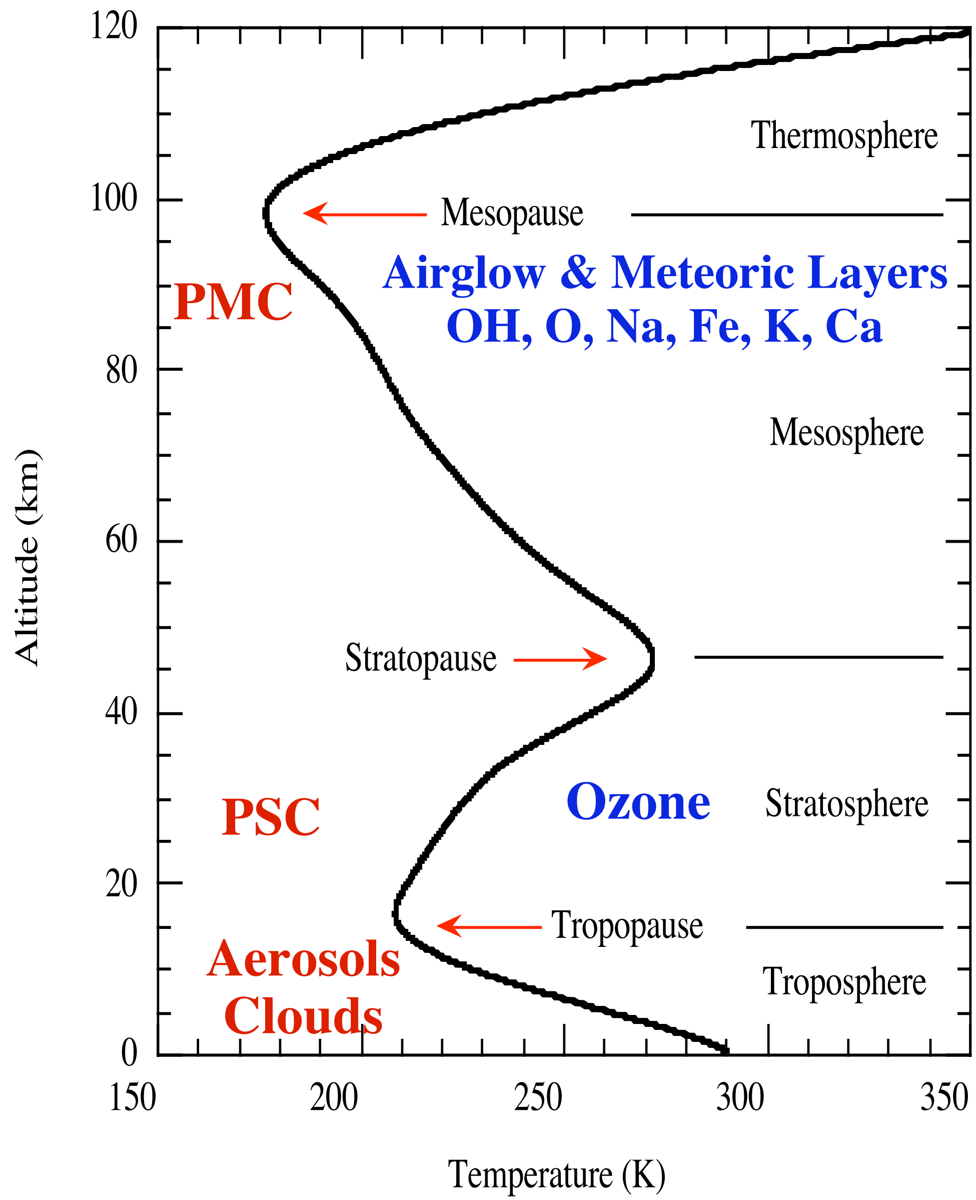
- 75-120km: resonance fluorescence (Na, K, Fe) Doppler technique (DDL)
- FPI: Fabry-Perot Interferometer
- Below 60km: Rayleigh Doppler technique (DDL)
- Below 30 km: Direct Detection Doppler technique
- In troposphere:

Coherent Detection Doppler tech,
Direct Detection Doppler tech,
Direct motion Detection tech
(tracking aerosols, LDV, LTV)

Comparison of Wind Techniques

Technique	Lidars	Applications
Doppler Wind Technique (Direct Detection or Coherent Detection): wind dependence of Doppler frequency shift (1 time Doppler shift for single absorption or emission process) (2 times Doppler shift for Mie and Rayleigh scattering)	Resonance Fluorescence Doppler Lidar: Doppler frequency shift and broadening of resonance fluorescence absorption cross-section (scan and ratio techniques)	Mesosphere and Lower Thermosphere temperature and wind (75-120 km)
	Rayleigh/Mie Doppler Lidar : Doppler frequency shift of molecular and aerosol scattering using edge filters and/or fringe imaging	Lower mesosphere, stratosphere and troposphere wind (up to 50-60 km)
	Coherent Detection Doppler Lidar: Doppler frequency shift of aerosol scattering using heterodyne detection tech	Troposphere wind, especially in boundary layers (up to 15 km), where aerosols are abundant
Direct Motion Detection Technique: derivative of displacement (the definition of velocity) (direct application of velocity definition or cross-correlation coefficient)	High-Spectral-Resolution Lidar: tracking aerosol / cloud motion through time	Troposphere wind, where aerosols and clouds are abundant
	(Scanning) Aerosol Lidar: tracking aerosol motion through time	Troposphere wind, where aerosols and clouds are abundant
	Laser Time-of-Flight Velocimeter: measuring time-of-flight of aerosol across two focused and parallel laser beams	Within the first km range, laboratory, machine shop, etc.
	Laser Doppler Velocimeter: measuring the frequency of aerosol scattering across the interference fringes of two crossed laser beams	Within the boundary layers, wind tunnel, production facility, machine shop, laboratory, etc

Aerosol Lidar Technique Comparison



- ❑ Aerosols in mesosphere (Mesospheric Clouds ~ 85 km): Rayleigh/Mie lidar, resonance fluorescence lidar (detuned)
- ❑ Aerosols in upper stratosphere (Polar Stratospheric Clouds ~ 20 km): Rayleigh/Mie lidar, resonance fluorescence lidar
- ❑ Aerosols in lower stratosphere and troposphere: Rayleigh/Mie elastic-scattering lidar, Raman scattering lidar, High-Spectral-Resolution Lidar (HSRL)

- ❑ In all altitude range, polarization & multi-wavelength detections help reveal aerosol microphysical properties

HSRL

- High-Spectral-Resolution-Lidar (HSRL) is to measure the molecule scattering separately from the aerosol scattering, utilizing the different spectral distribution of the Rayleigh and Mie scattering.

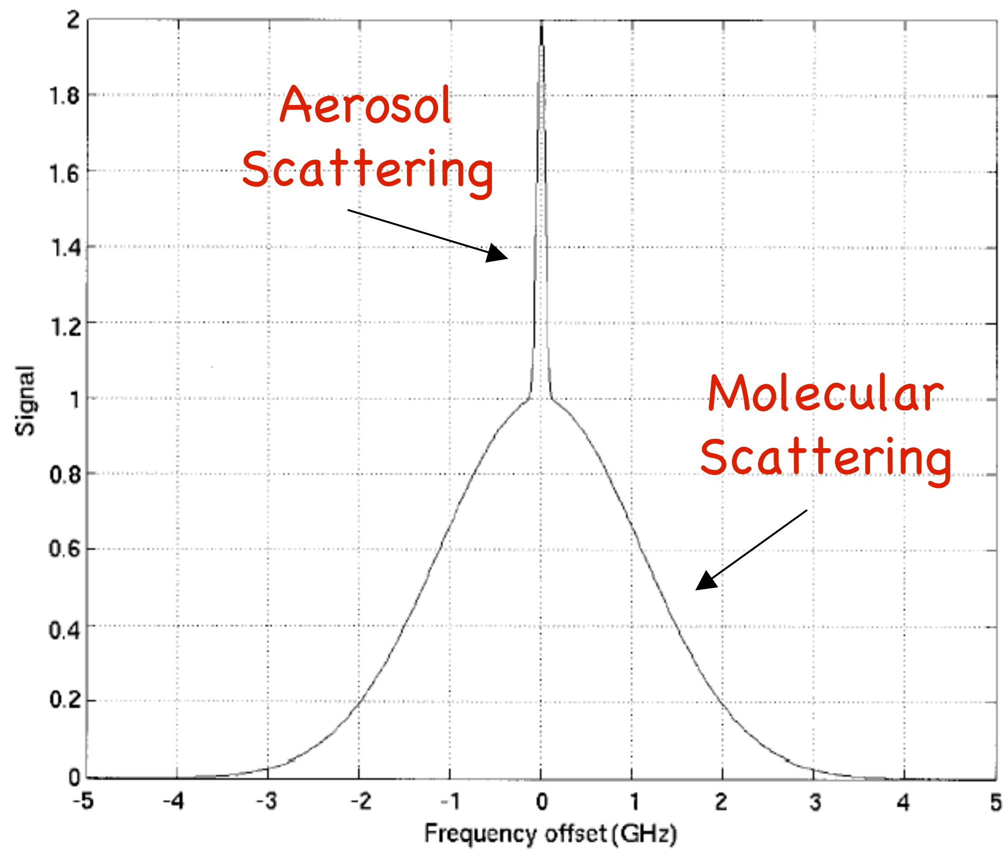
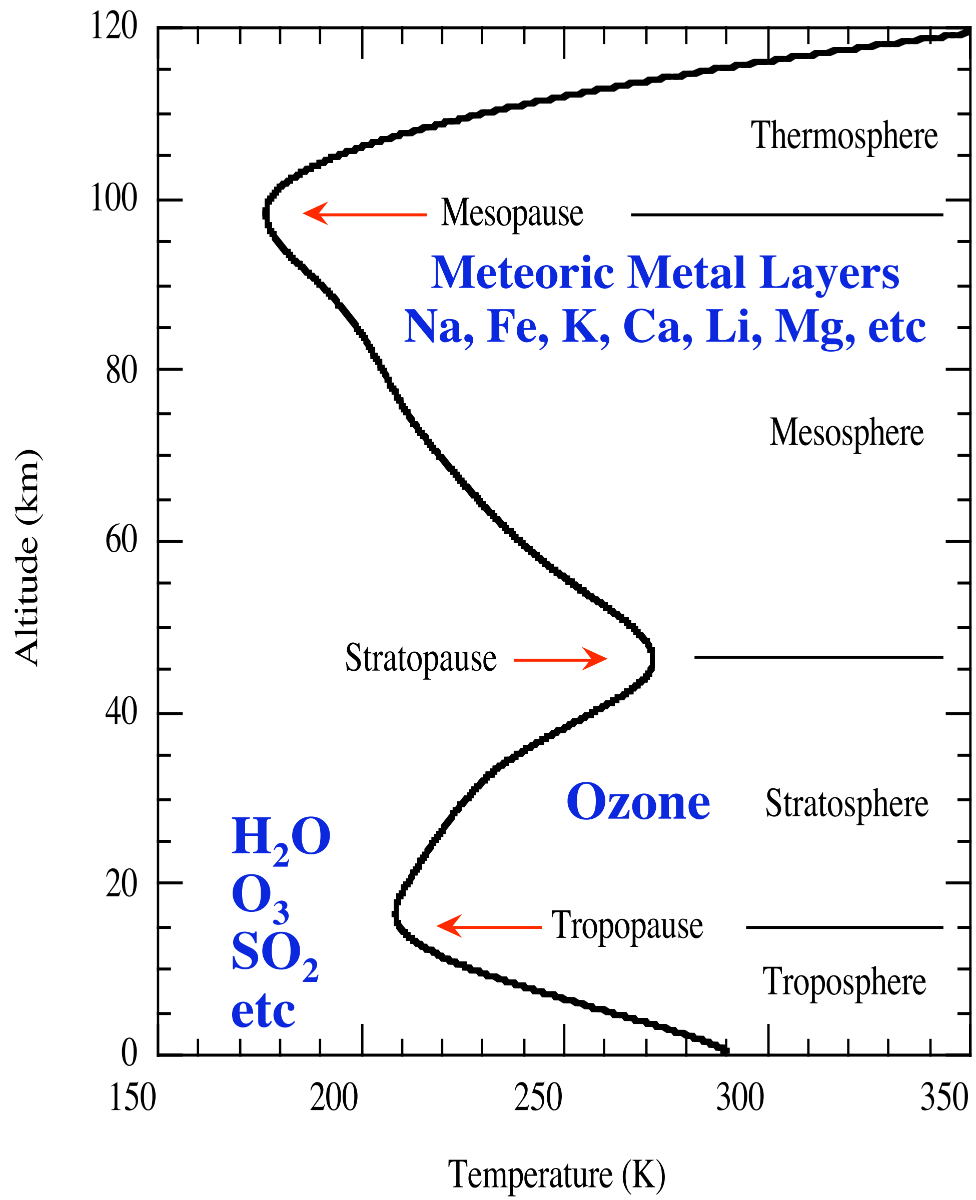


Fig. 5.1. Spectral profile of backscattering from a mixture of molecules and aerosols for a temperature of 300 K. The spectral width of the narrow aerosol return is normally determined by the line width of the transmitting laser.

Constituent Lidar Techniques



- ❑ He and N_2^+ in thermosphere: resonance fluorescence lidar
- ❑ O in thermosphere: resonance fluorescence lidar or DIAL from space
- ❑ Metal atoms in 75-120km: resonance fluorescence lidar (broadband or narrowband transmitter)
- ❑ Molecular species in lower stratosphere & troposphere: Differential absorption lidar (DIAL), Raman scattering lidar, Raman DIAL, RVR Raman DIAL, Multiwavelength DIAL

- ❑ The key is to use spectroscopic detection for distinguish species.

Comparison of Constituent Lidar Tech

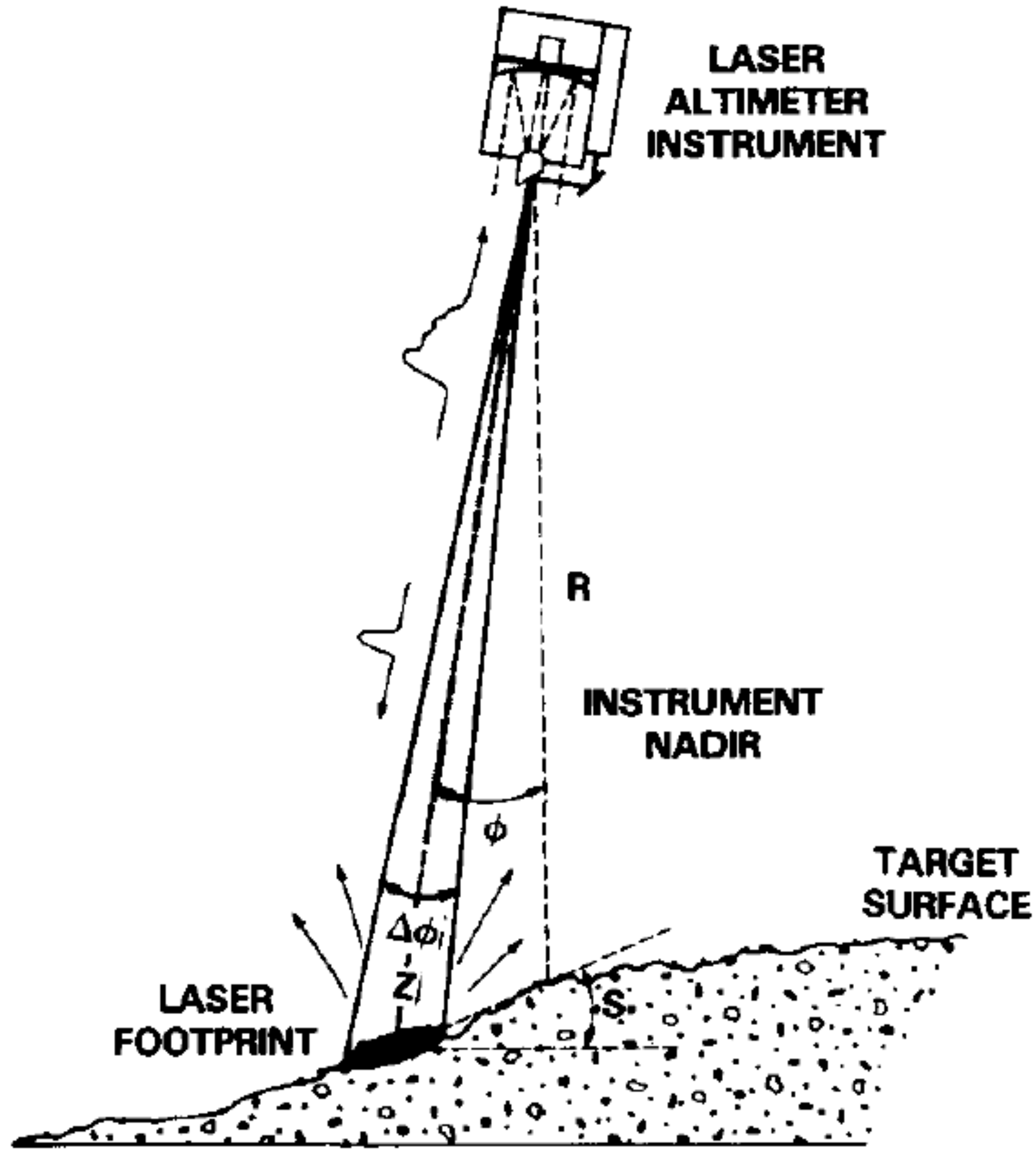
Technique	Signal Source & Trace Gas		Interests
Resonance Fluorescence Lidar	Resonance fluorescence from metal atoms in middle and upper atmosphere		Temp, Wind, Density, Wave
Resonance Fluorescence Lidar	Resonance fluorescence from He, N_2^+, O in thermosphere		Density, Temp Wind, etc
Conventional DIAL	Elastic-scattering from air molecules and aerosols	Trace gas absorption in the extinction terms	Species, Density
Raman Lidar	Inelastic Raman scattering from trace gas and reference N_2 or O_2	Trace gas scattering in the backscatter terms (no aerosol scattering)	Species, Density, Mixing ratio
Raman DIAL	Inelastic Raman scattering from N_2 or O_2	Trace gas absorption in the extinction terms	Species, Density
RVR Raman DIAL	Pure rotational Raman scattering and Vibrational-Rotational Raman scattering	Trace gas absorption in the extinction terms	Species, Density
Multiwavelength DIAL	Elastic scattering from air molecules and aerosols	Trace gas absorption in the extinction terms	Species, Density

Range-Resolved spatial & temporal distribution of these species, density, temp, wind and waves

Laser Altimeter (Laser Ranging)

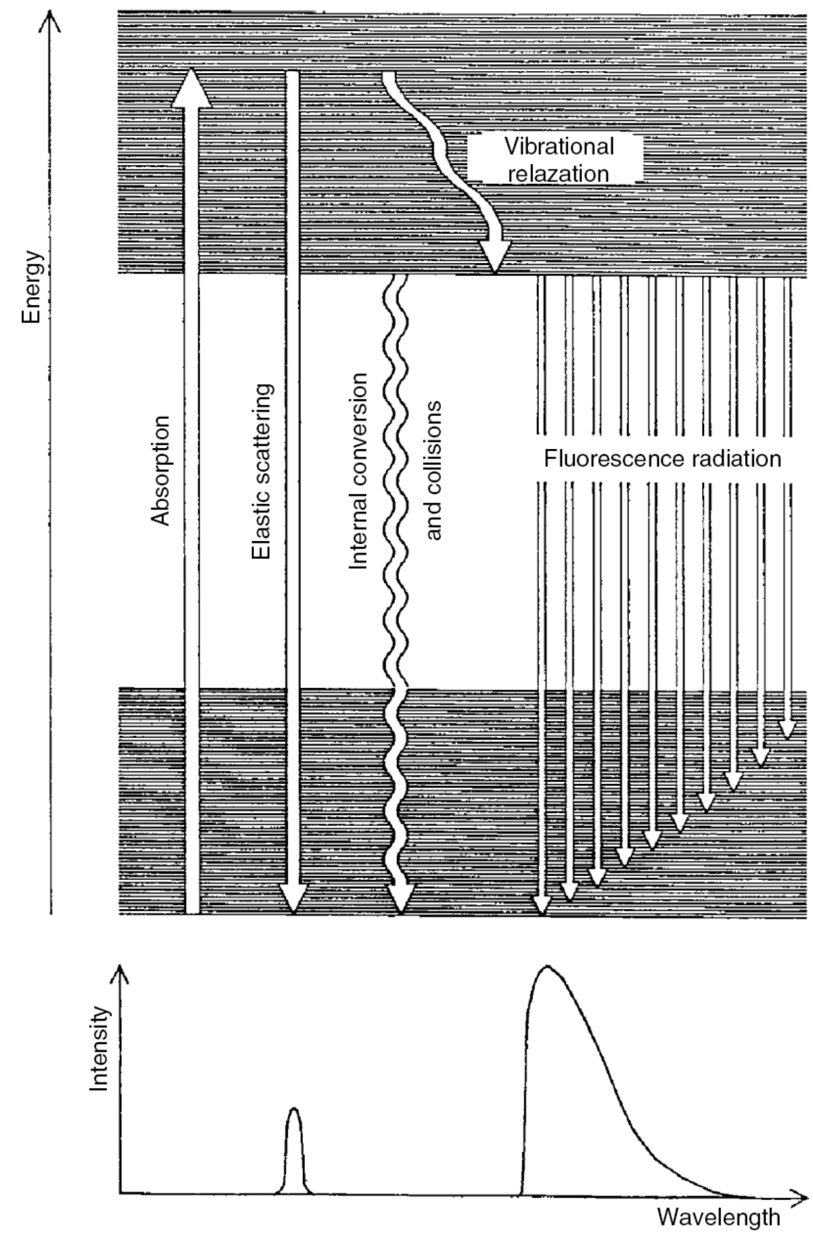
- The time-of-flight information from a lidar system can be used for laser altimetry from airborne or spaceborne platforms to measure the heights of surfaces with high resolution and accuracy.

- The reflected pulses from the solid surface (earth ground, ice sheet, etc) dominant the return signals, which allow a determination of the time-of-flight to much higher resolution than the pulse duration time.



Fluorescence from Liquids and Solids

- In contrast to free atoms and molecules, solids and liquids exhibit broad absorption and emission spectra because of the strong intermolecular interactions.
- A fixed frequency laser can be used for the excitation due to the broad absorption.
- Following the excitation, there is a very fast (ps) radiationless relaxation down to the lowest sub-level of the excited state, where the molecules remain for a typical excited-state fluorescence lifetime.
- The decay then occurs to different sub-levels of the ground state giving rise to a distribution of fluorescence light, which reflect the lower-state level distribution.
- Fixing the excitation wavelength, we can obtain fluorescence spectra. While fixing the detection channel and varying the excitation wavelength, an excitation spectrum can be recorded.

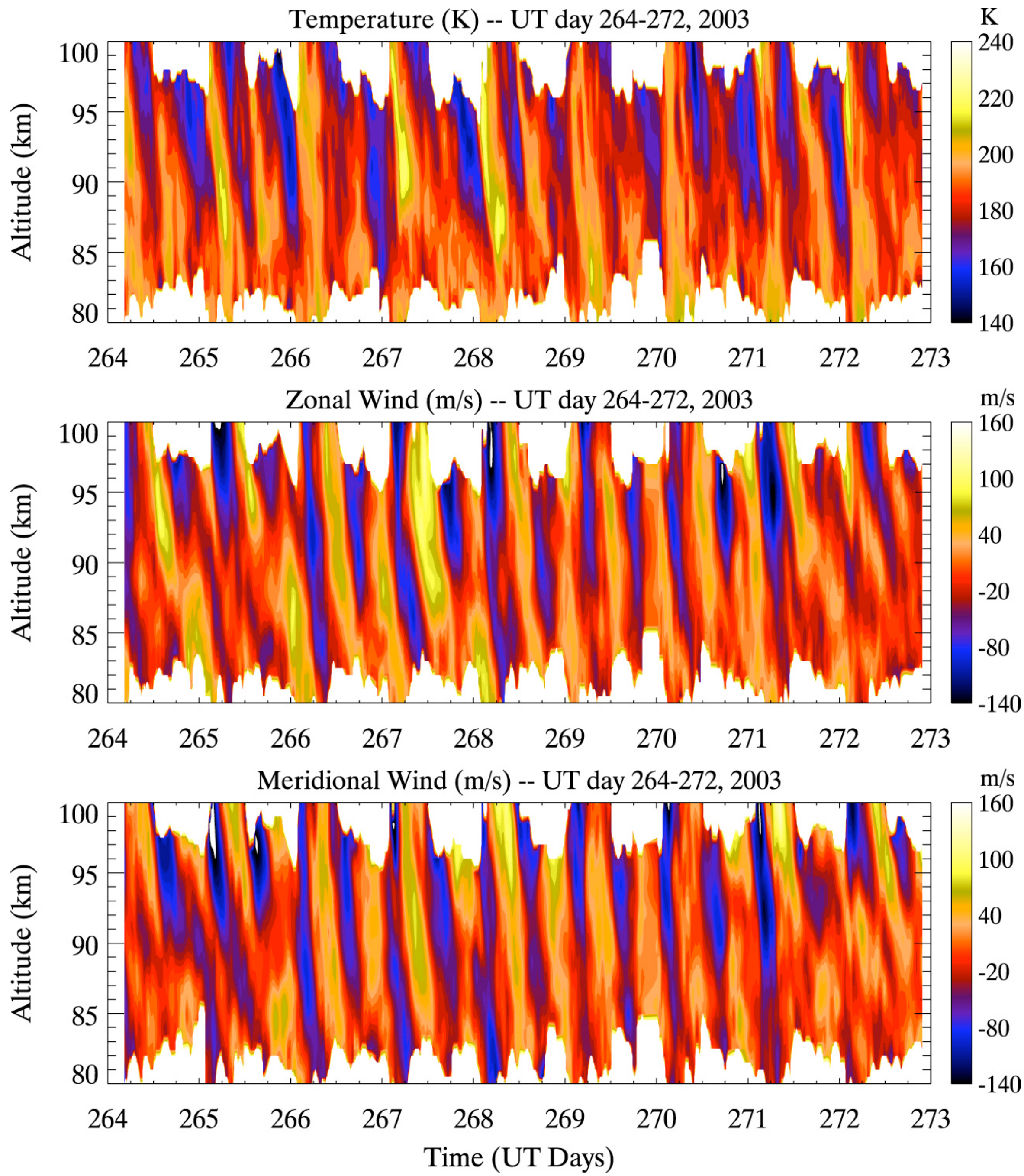


Summary

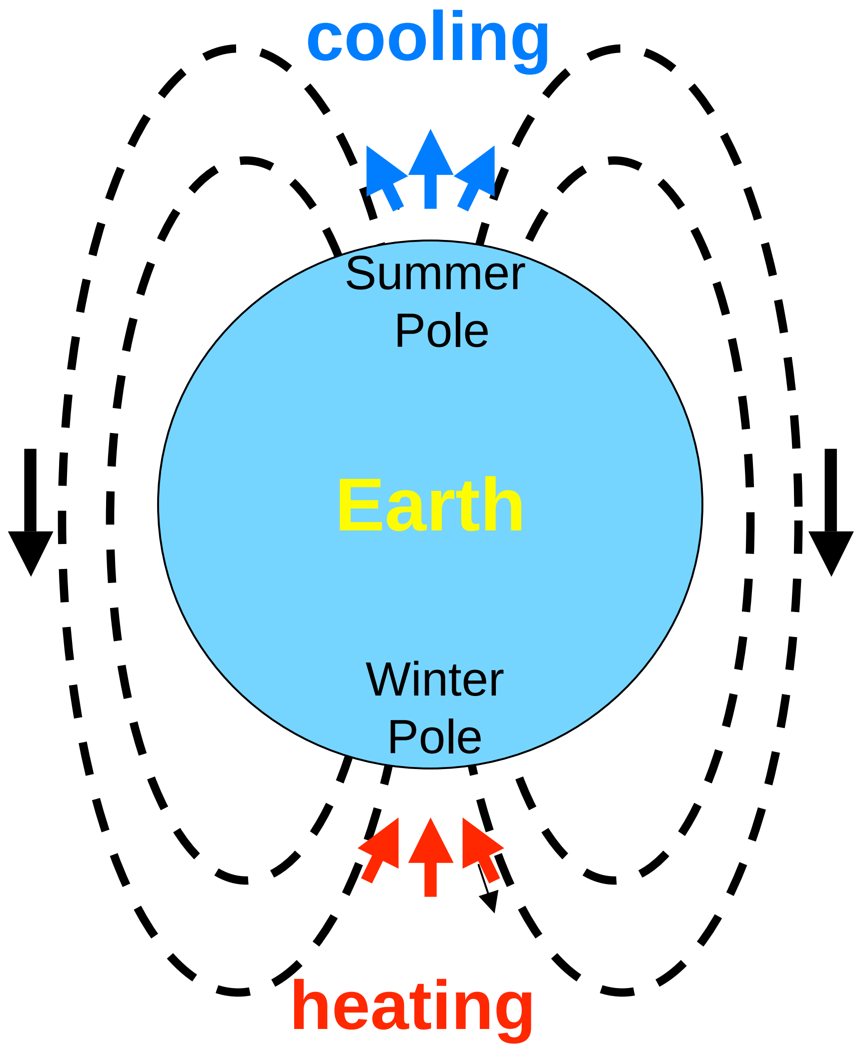
- Five major topics are chosen for reviewing lidar measurement principles and technologies: temperature, wind, aerosol, constituent, and target/altimeter.
- For each topic, various technologies will be compared to reveal the key ideas behind the lidar technologies.
- Real lidar data for some of the topics will be given for students to perform data inversion, i.e., from raw photon counts to meaningful physical parameters.
- Data inversion principles and procedures will be explained along the way.

Motivations For T/W Measurement

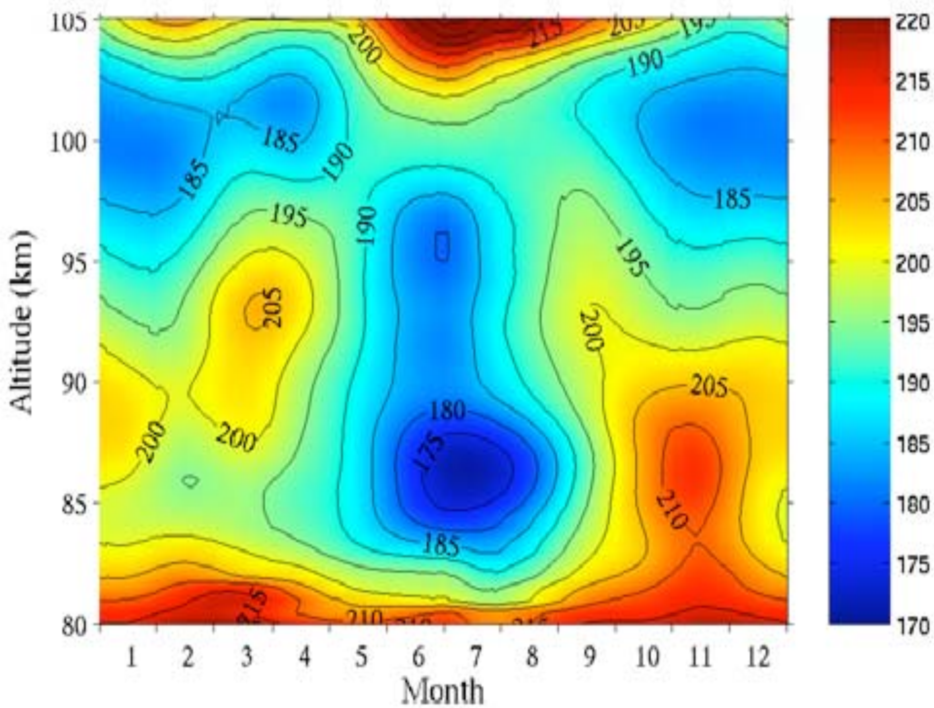
- Model validations
- Atmospheric dynamics study
- Global climate change monitoring
- Proxy to study gravity waves, tides, planetary waves, etc. dynamical processes



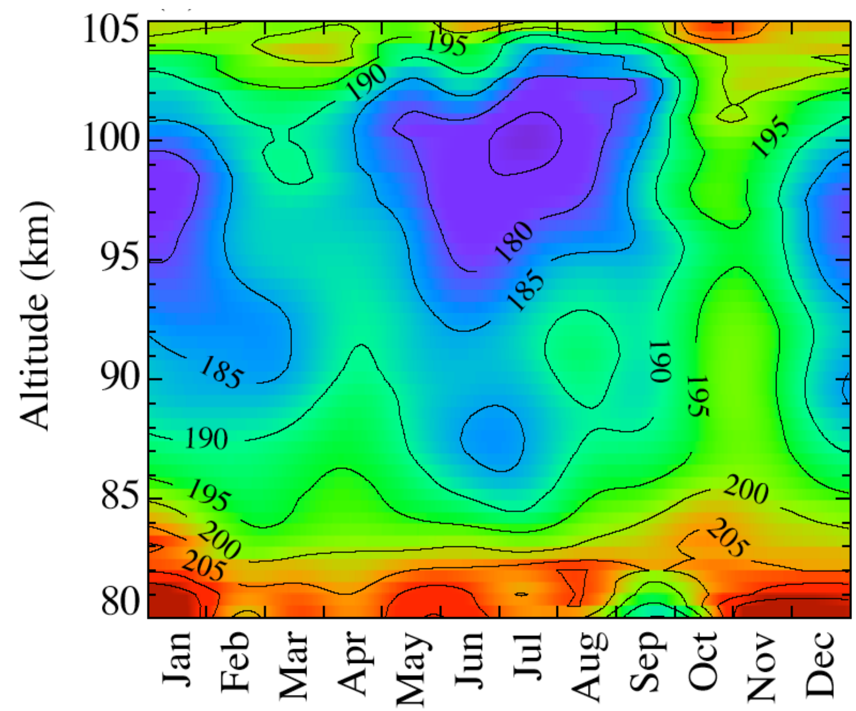
General Circulation versus Global Thermal Structure



Circulation versus Other Mechanisms



Lidar Temperature at Albuquerque, NM (35°N)



Lidar Temperature at Arecibo, PR (18.35°N)