The Vertical Structure of the Atmosphere and Model Levels

Lecture 6

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Lecture Objective and Learning Outcomes

Lecture objective

To explain the vertical structure of the atmosphere and the vertical coordinate of WRF, and to show how to analyse profiles, stability and boundary-layer height from model output.

Learning outcomes

By the end of this lecture, students will be able to:

1. explain why WRF uses terrain-following hybrid levels and how they are distributed with height;
2. obtain the height, pressure and potential temperature of the model levels with getvar;
3. distinguish temperature from potential temperature and assess static stability from a θ profile;
4. extract and plot a vertical profile at a point and determine the boundary-layer height;
5. interpolate fields to pressure levels with interplevel and recognise where a level lies below the ground.

From Maps to the Third Dimension

- Lecture 5: maps show the atmosphere from above
- Today: profiles and levels, because many key processes are vertical

Temperature inversions

Warm air above cold air: pollution is trapped near the ground

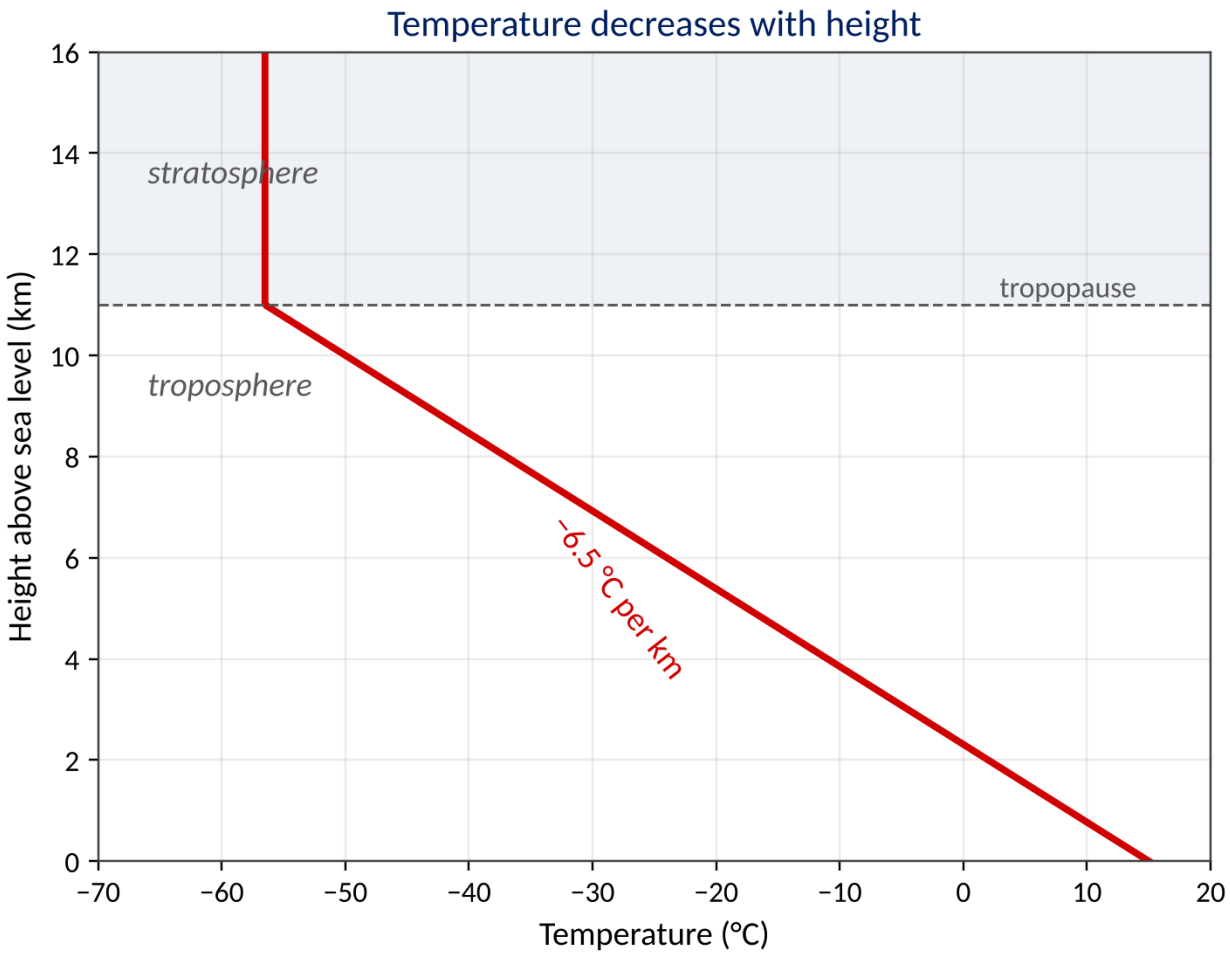
Boundary-layer height

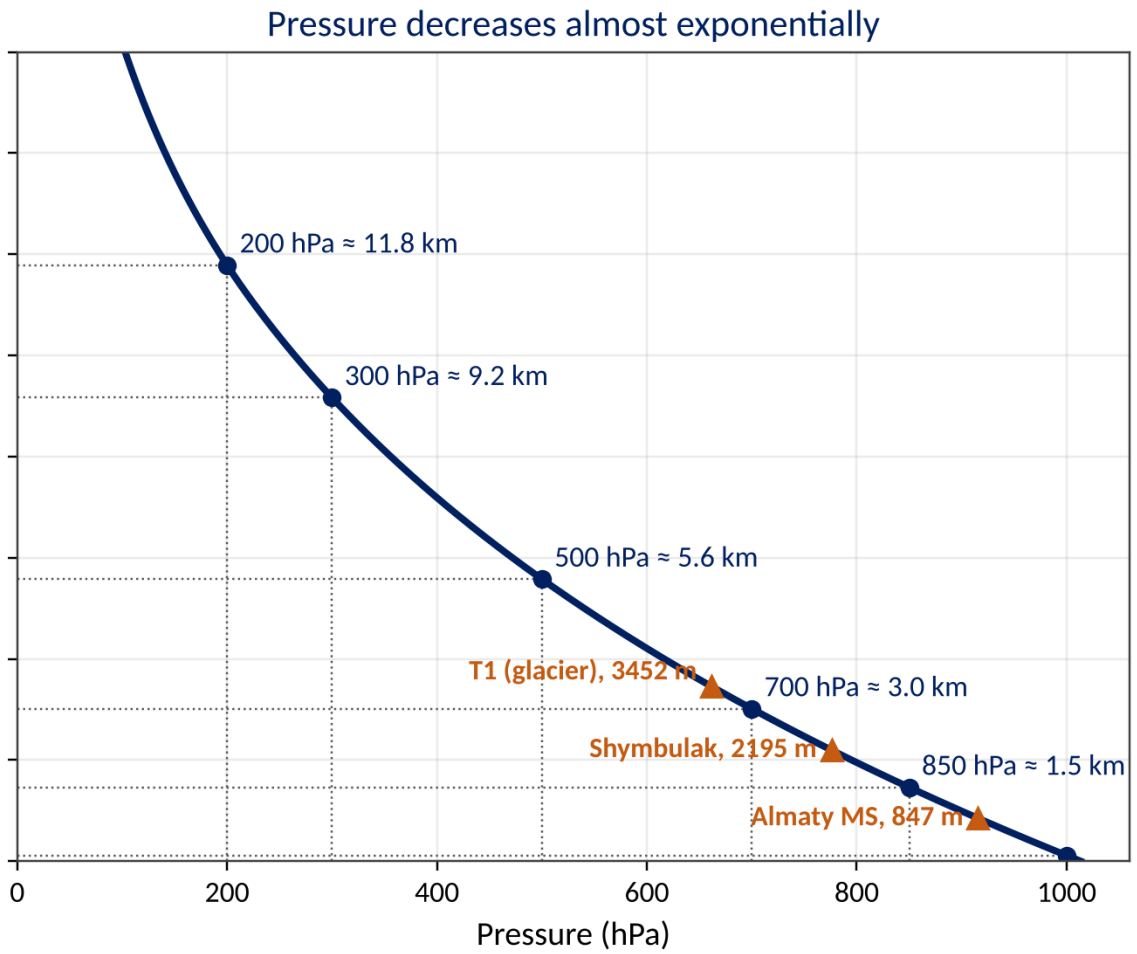
The volume in which emissions are mixed: 200 m instead of 1 km means 5 times the concentration

Wind changes with height

Pollution at different heights travels in different directions

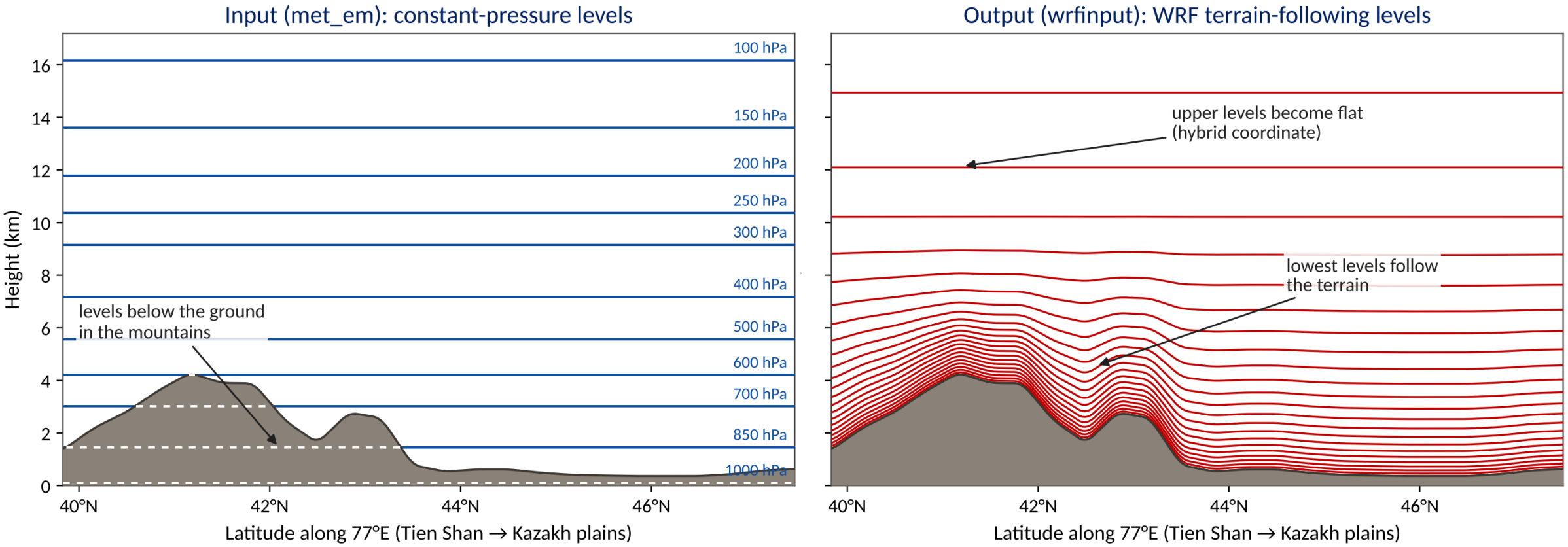
Pressure and Temperature: the Standard Atmosphere





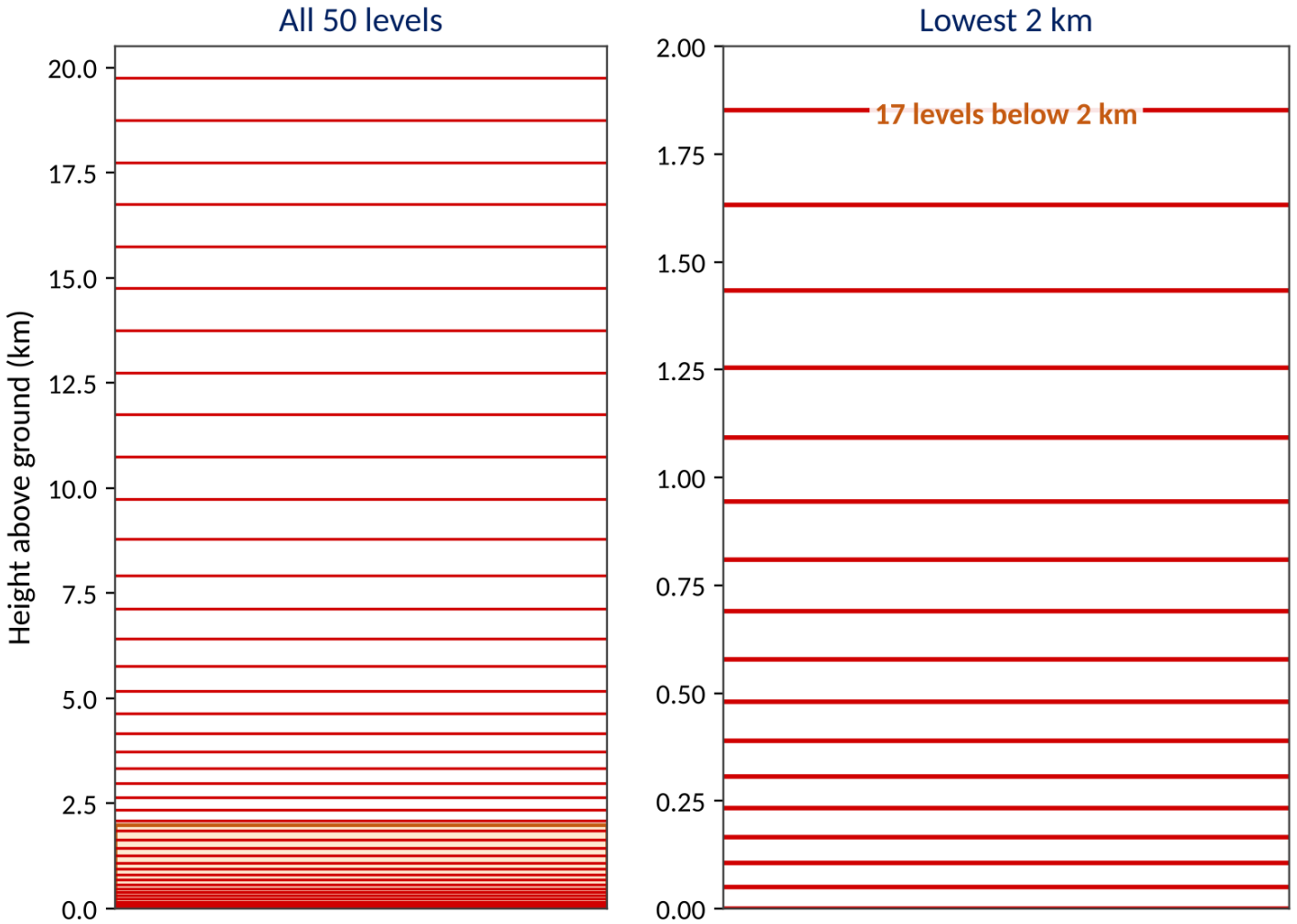
Station altitudes: Tursumbayeva et al. (2026), Meteorological Applications, 33, e70183

Vertical Coordinates



Pressure levels pass below the ground in mountains; WRF levels follow the terrain and become flat aloft (hybrid coordinate)

Model Levels in WRF



Illustrative distribution of 50 levels (lowest layer 50 m, model top about 20 km)

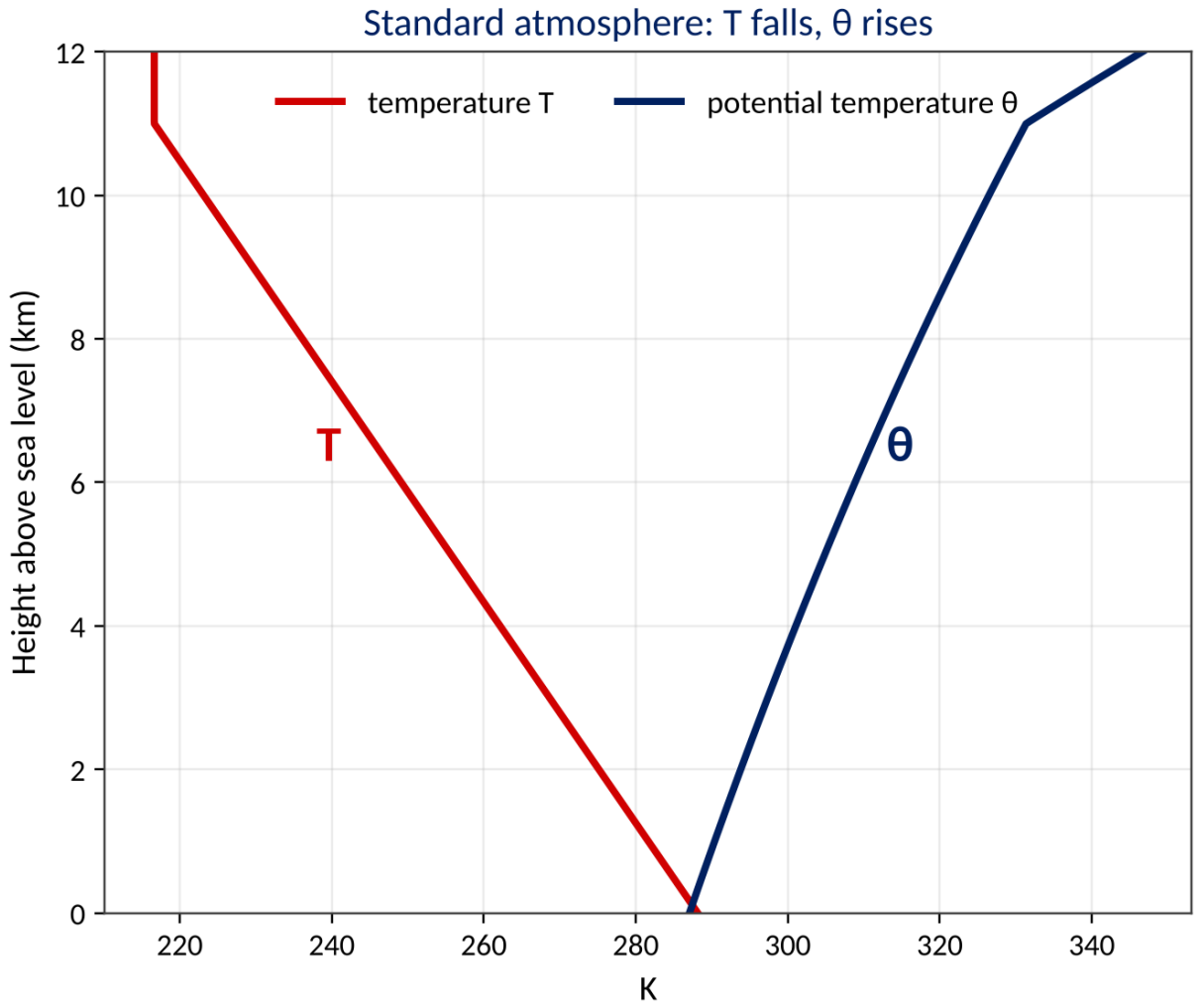
- The user chooses the number of levels
- 50 levels in our Almaty study
- Dense near the ground, sparse aloft
- A third of the levels in the lowest 2 km
- A level number is not a height

Height and Pressure of Model Levels in Python

```
from wrf import getvar

z   = getvar(nc, "z")            # above sea level, m
agl = getvar(nc, "height_agl")   # above the ground, m
p   = getvar(nc, "pressure")     # hPa
th  = getvar(nc, "theta")        # potential temp., K

print(z.shape)                   # (49, 145, 226)
```

- getvar combines base state and perturbation for us
- 3-D arrays: levels × south_north × west_east
- z: compare with pressure maps and soundings
- height_agl: use for the boundary layer

Temperature and Potential Temperature

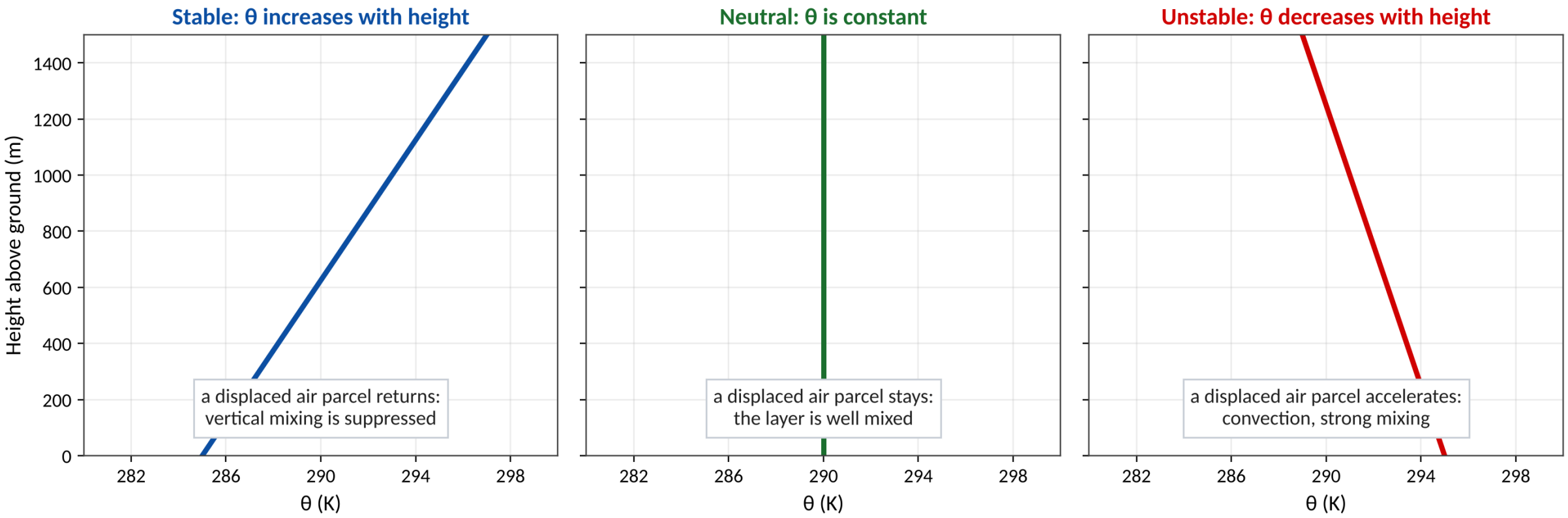


$$\theta = T \cdot (1000 / p)^{0.286}$$

- T in K, p in hPa

- Rising air expands and cools: T alone says nothing about stability
- θ: the temperature of a parcel brought adiabatically to 1000 hPa
- θ is conserved in adiabatic motion

Static Stability



Read the slope of the θ profile: to the right = stable, vertical = mixed, to the left = unstable

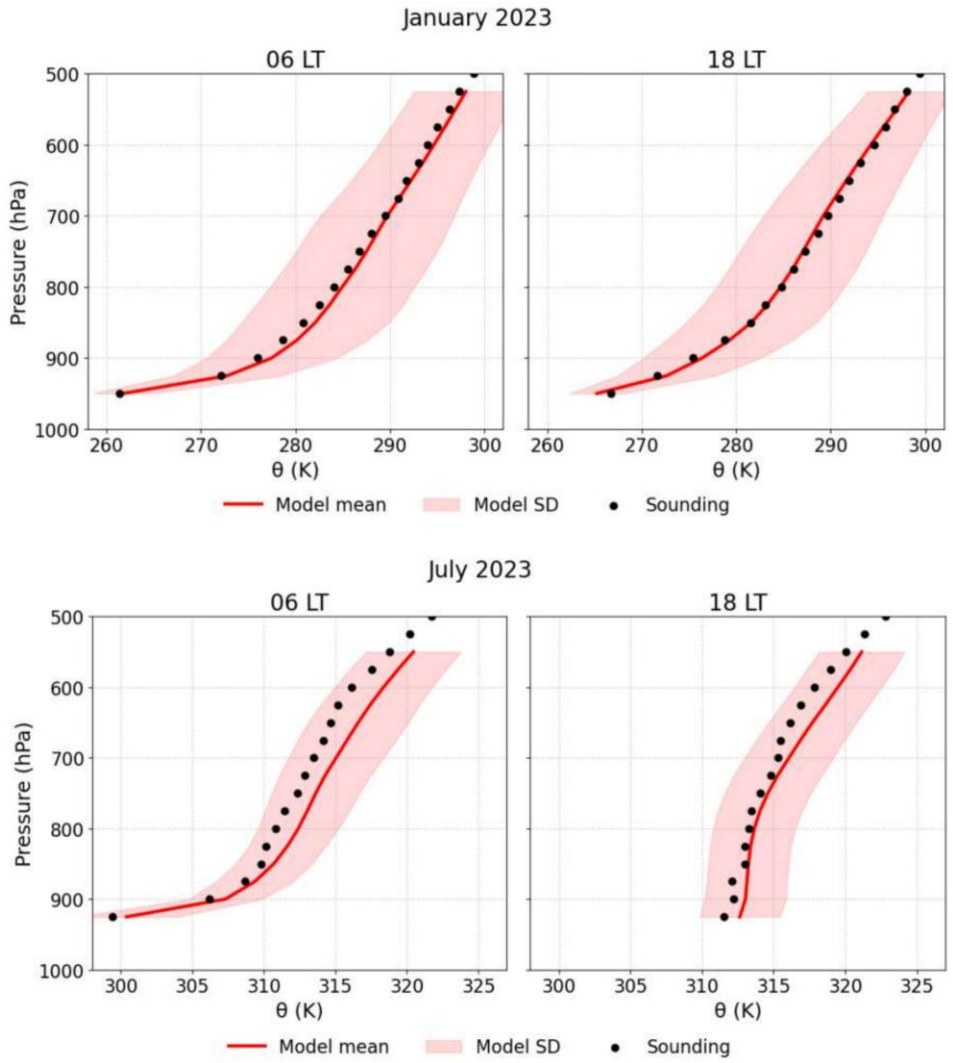
- A temperature inversion is a case of very strong stability

A Vertical Profile at a Point

```
from wrf import getvar, ll_to_xy, to_np

# column nearest to the Almaty aerological station
x, y = ll_to_xy(nc, 43.36, 77.00)

th_prof = to_np(th[:, y, x])     # all levels, one column
z_prof  = to_np(agl[:, y, x])

plt.plot(th_prof, z_prof)
plt.xlabel("Potential temperature (K)")
plt.ylabel("Height above ground (m)")
plt.ylim(0, 3000)
```

- A profile = all levels in one model column
- ll_to_xy: the column nearest to the station
- [:, y, x]: every level at this point
- Height is always on the vertical axis

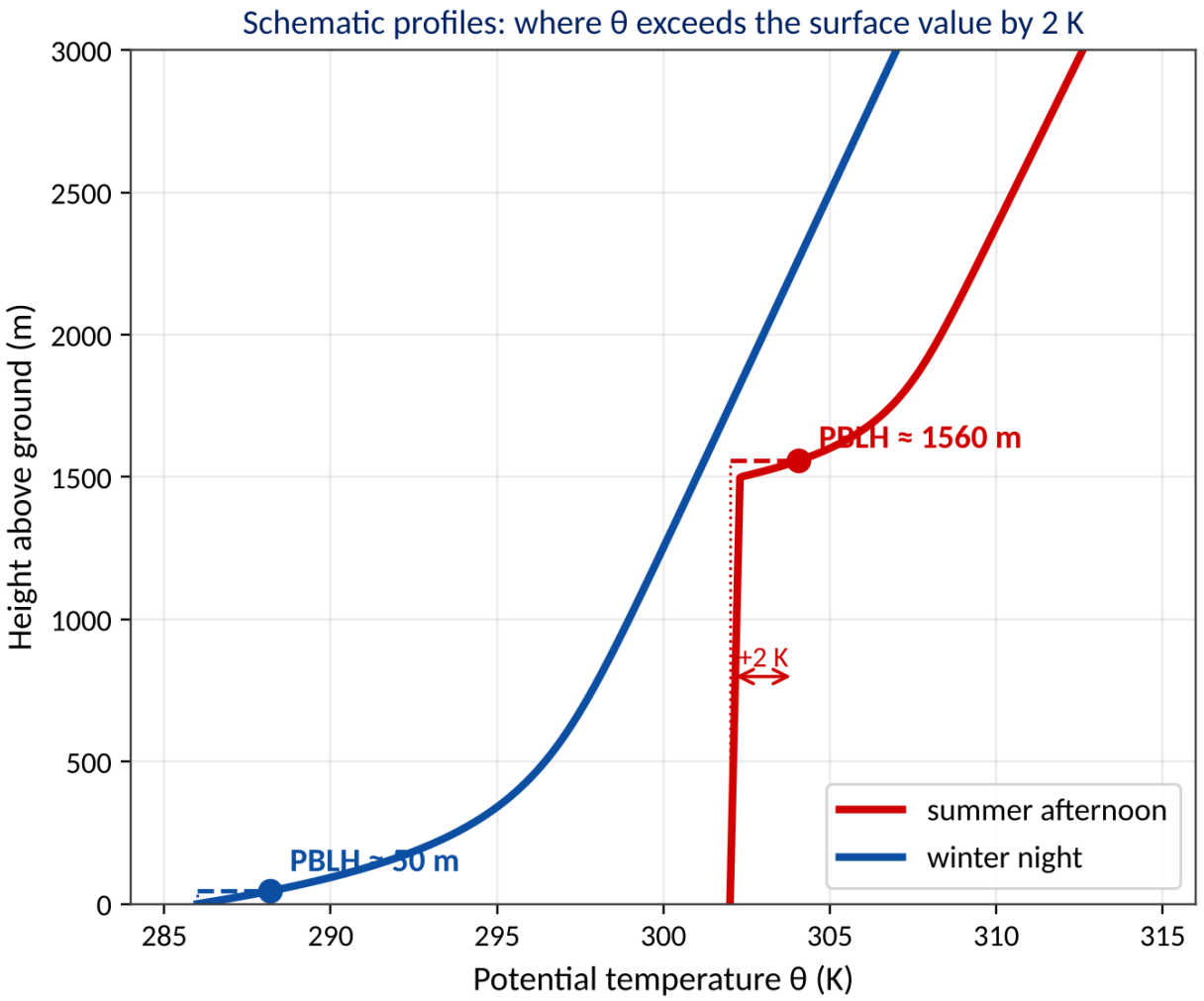
Research Example: Potential Temperature over Almaty



- Model (red) and radiosonde (black) at the Almaty aerological station, 06 and 18 local time
- Index of agreement: 0.99 in January; 0.91 and 0.86 in July
- January: θ rises sharply near the surface: a strong inversion, morning and evening
- July, 18 LT: almost vertical profile below: a well-mixed layer

Source: Tursumbayeva et al. (2026), Meteorological Applications, 33, e70183

The Planetary Boundary Layer Height (PBLH)



Potential temperature method

The level where θ first exceeds its surface value by more than 2 K

Bulk Richardson number

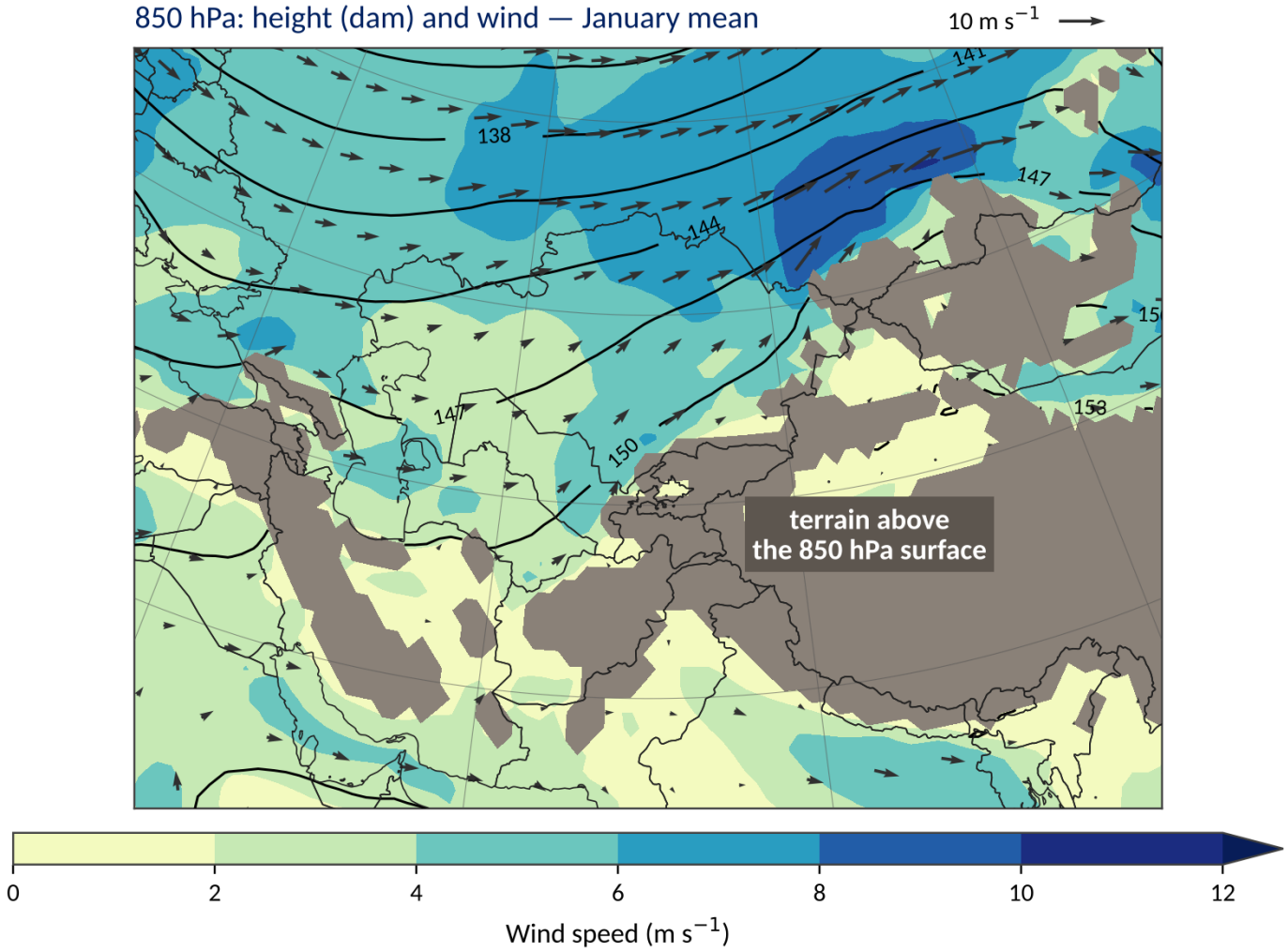
The lowest level where Ri exceeds 0.25 (stability + wind shear)

WRF output

The variable PBLH, calculated by the boundary-layer scheme

Methods as in Tursumbayeva et al. (2026))

From Model Levels to Pressure Levels

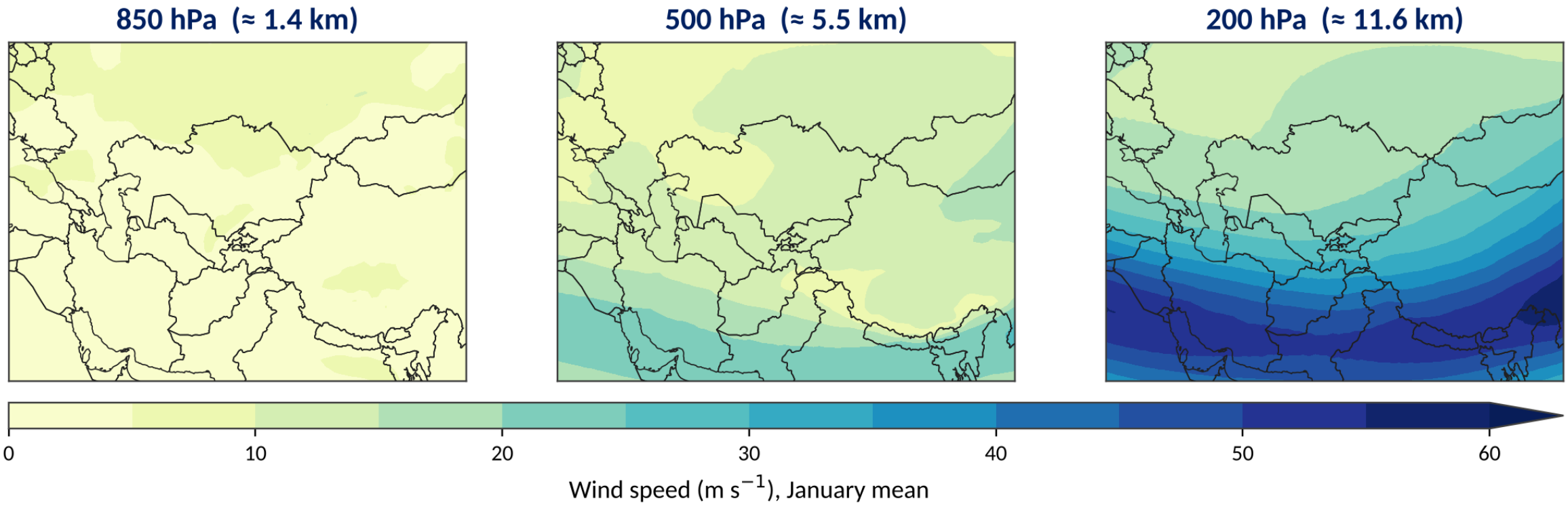



```
from wrf import interplevel

tc = getvar(nc, "tc")    # °C
t850 = interplevel(tc, p, 850.)
z850 = interplevel(z, p, 850.)
```

- interplevel: a 3-D field on one pressure level
- Grey: the 850 hPa surface is below the ground
- In mountains use 700 hPa or model levels

Data: ERA-Interim reanalysis, monthly means (xarray tutorial dataset)

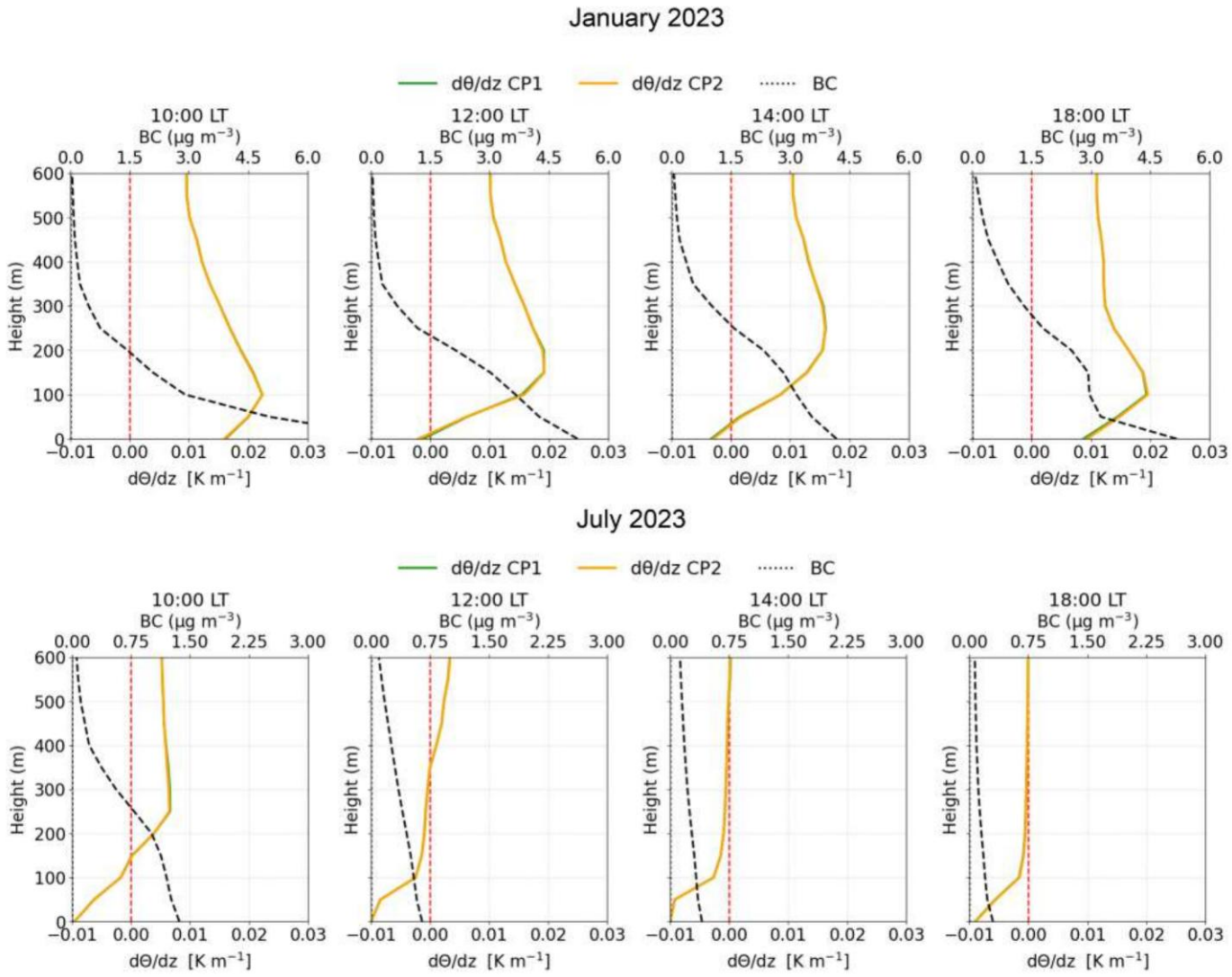
The Atmosphere at Three Levels



Lower troposphere: transport. Middle: steering flow. Upper: jet stream. Always look at several levels

Data: ERA-Interim reanalysis, monthly means (xarray tutorial dataset)

Research Example: Black Carbon and Stability Profiles



- Lowest 600 m above Almaty; dashed: BC, solid: dθ/dz
- January: stable at all hours; BC stays in the lowest 200–300 m
- July, daytime: dθ/dz near zero: well mixed, low BC
- With and without BC–radiation feedback: stability differs by less than 2 %

Source: Tursumbayeva et al. (2026), Meteorological Applications, 33, e70183

Four Typical Mistakes

A level number is not a height

Always calculate the real height or pressure of the levels

Sea level or ground?

z is above sea level; height_agl is above the ground

T is not θ

Never judge stability from a temperature profile alone

Pressure levels below the ground

In mountains 850 hPa may not exist: treat the values as missing

Radiosondes: 00 and 12 UTC = 06 and 18 local time in Almaty (2023); the model has output for every hour

Summary

Key points

- WRF levels follow the terrain and are densest near the ground
- getvar gives the height, pressure and θ of every level
- θ increasing with height = stable; constant = mixed
- The θ profile gives the boundary-layer height
- interplevel: from model levels to pressure levels

Next lecture

Vertical cross-sections

Combining the horizontal and the vertical

Thank you for your attention!

Self-Check Questions

1. Why is a model level number not a height?
2. What is the difference between z and height_agl, and when is each of them used?
3. Why is potential temperature, and not temperature, used to judge stability?
4. How do stable, well-mixed and unstable layers look in a θ profile?
5. Which three ways of determining the boundary-layer height were discussed?
6. Why can the 850 hPa level be unusable in mountain areas?

References

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9. Figure data: ERA-Interim monthly means from the xarray tutorial datasets (github.com/pydata/xarray-data); NOAA NGDC ETOPO global relief model; Natural Earth.