Air Quality–Meteorology Interactions and Sensitivity Analysis

Lecture 10

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Lecture Objective and Learning Outcomes

Lecture objective

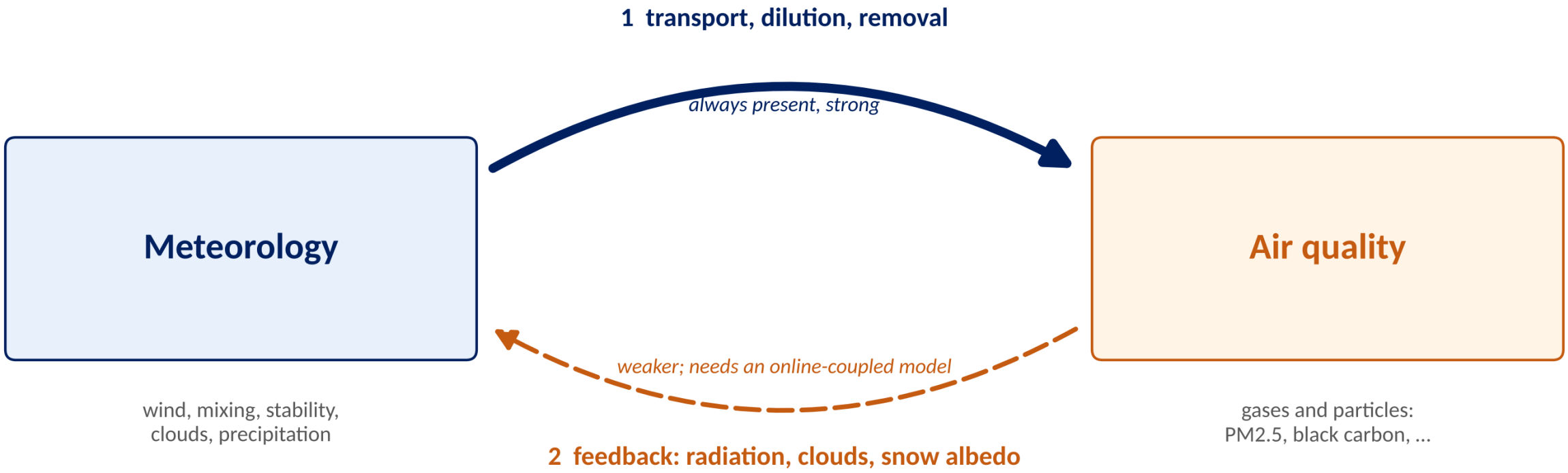
To explain the two-way interactions between meteorology and air pollution and to show how a sensitivity analysis with a coupled model measures them, using black carbon in Almaty as an example.

Learning outcomes

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

1. explain how wind, boundary-layer height, stability and precipitation control pollution;
2. describe the direct radiative effect of black carbon and the possible feedback loop;
3. design a sensitivity experiment in which only one factor is changed;
4. interpret the radiative metrics: the effect at the surface, within the atmosphere and at the top of the atmosphere;
5. assess a sensitivity result critically: effect or noise, conditions and simplifications.

Two Directions of Interaction



- Direction 1: always present; explains most of the variability of pollution
- Direction 2: the question of this lecture: how strong is it in a real city?

Direction 1: How Meteorology Controls Pollution

Wind

Ventilation: carries pollution away

Boundary-layer height

The volume in which emissions are mixed

Stability

An inversion is a lid on the pollution

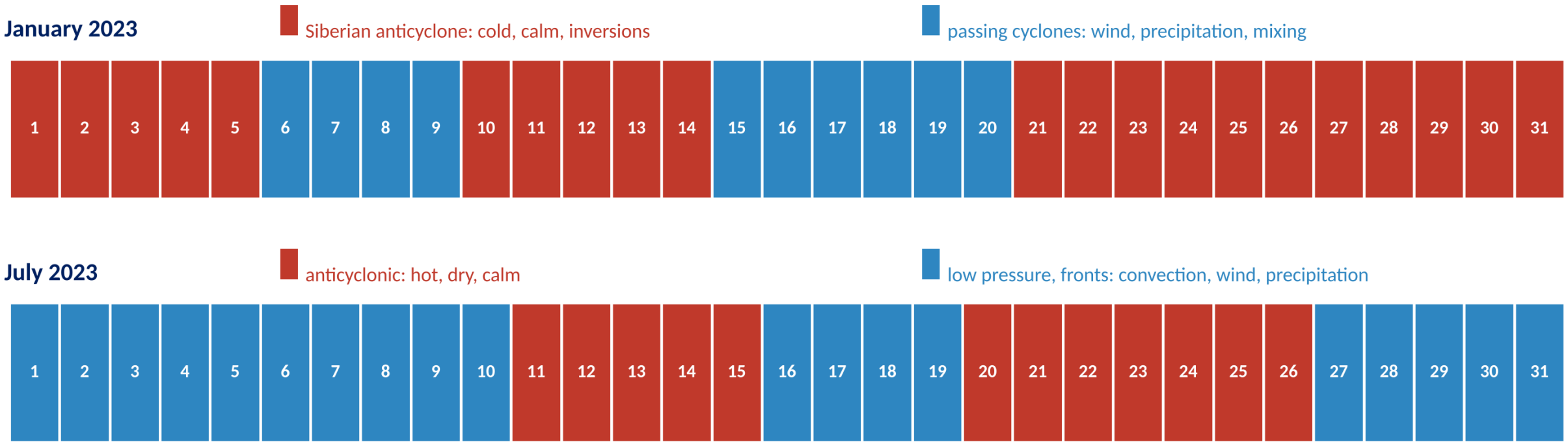
Precipitation

Washes pollutants out of the air

And temperature changes the emissions themselves: more heating in cold weather

- Almaty in winter: weak wind, shallow boundary layer, strong inversions, little precipitation, maximum heating
- Daily PM2.5 can exceed 200 µg m^{-3}

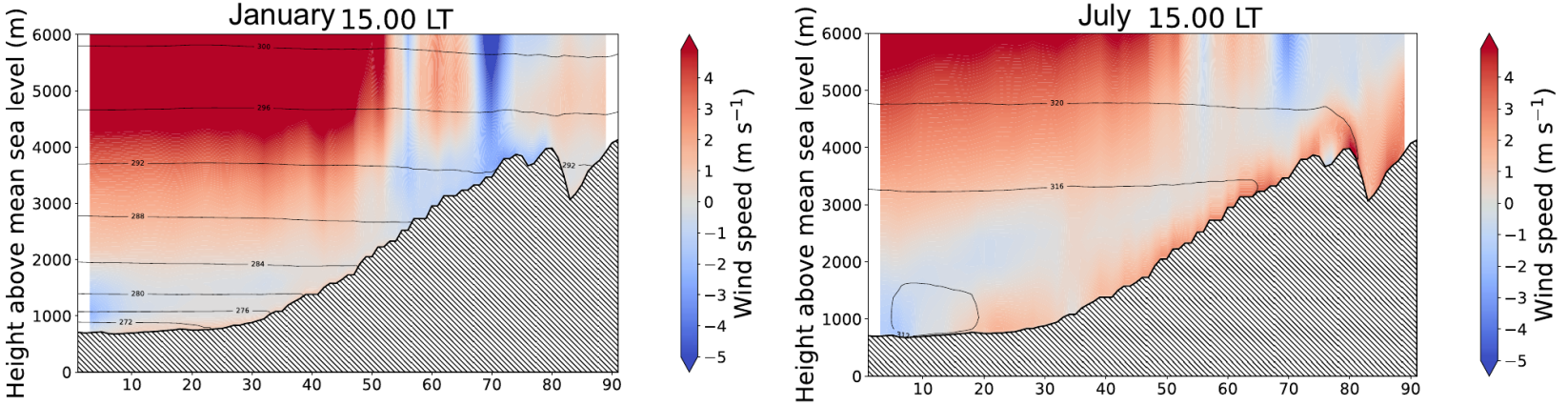
The Synoptic Context: January and July 2023



- Red: conditions for accumulation of pollution. Blue: conditions for dispersion
- Always check the synoptic situation before analysing an air quality simulation

Periods as described in Tursumbayeva et al. (2026), Meteorological Applications, 33, e70183

The Local Circulation: Mountain–Valley Wind



Red: upslope flow

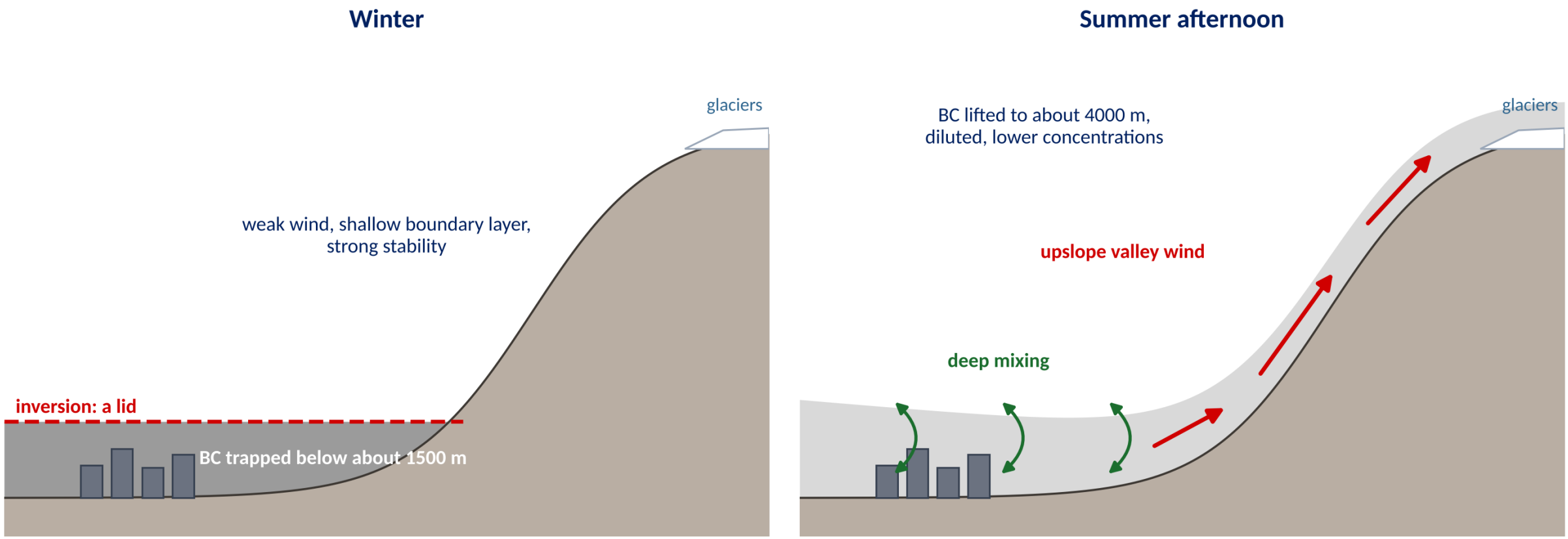
January: weak circulation, strong stratification

July: upslope flow up to about 4000 m

The main path by which air leaves a basin at the foot of the mountains

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

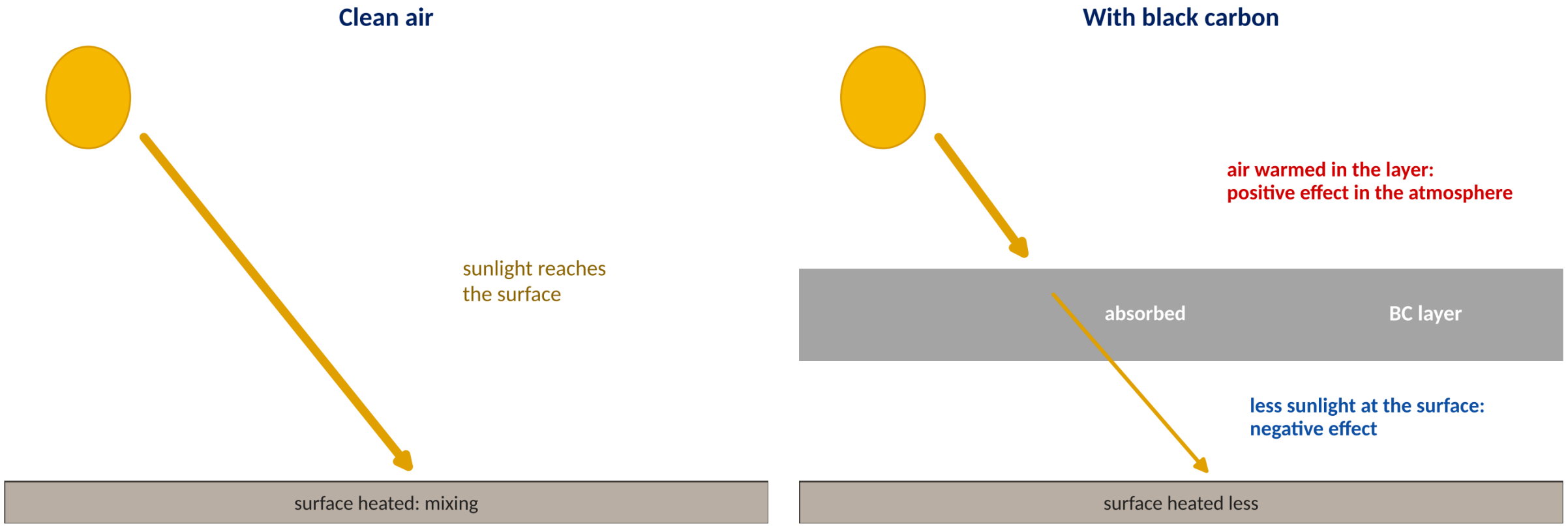
The Result of Direction 1: Winter and Summer



Winter: a problem for the health of the city. Summer: a possible effect on glaciers and water resources

Schematic summary of the results of Tursumbayeva et al. (2026), Meteorological Applications, 33, e70183

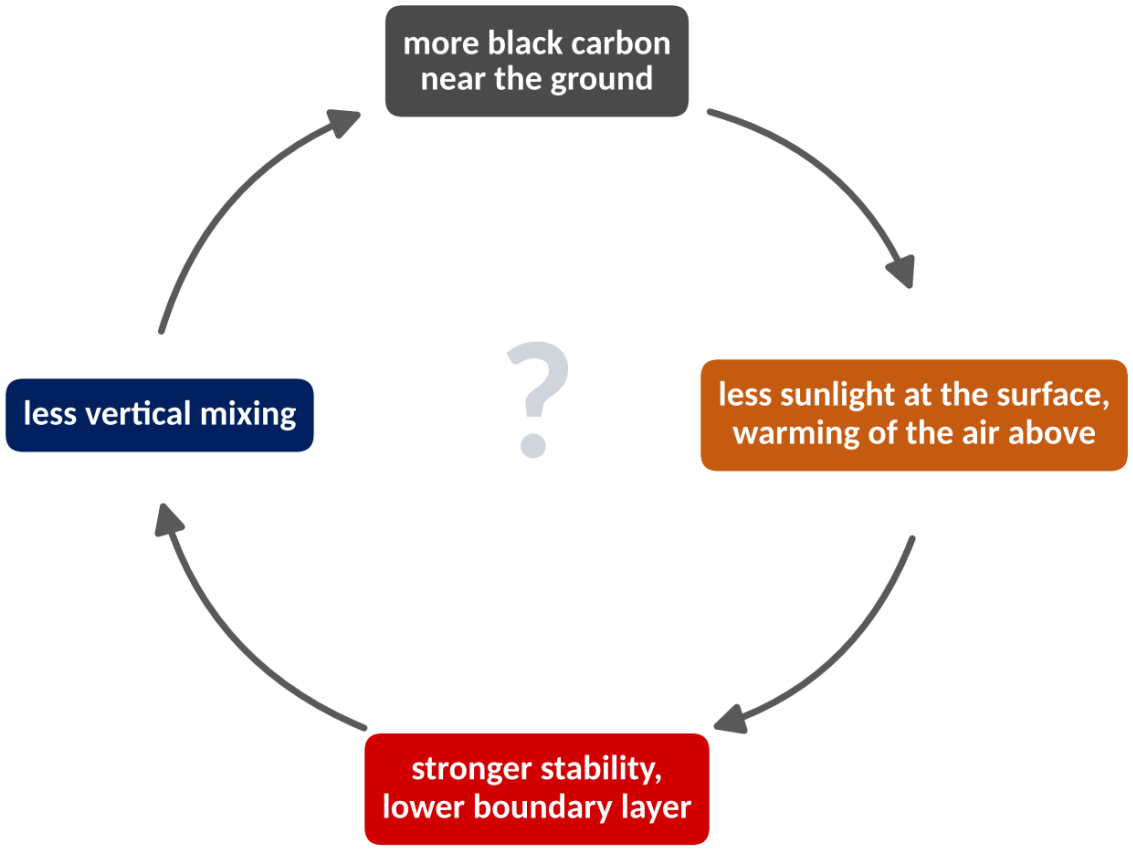
Direction 2: How Black Carbon Changes Radiation



Direct radiative effect: positive within the atmosphere, negative at the surface

- Other pathways: clouds (indirect effect), darker snow and ice

A Possible Feedback Loop



Pollution could make the weather more favourable for pollution

- Described for strongly polluted regions
- Does it work in Almaty? How strong is it?
- Observations cannot answer: we cannot switch black carbon off
- A model can

What Is a Sensitivity Analysis?

Two runs, identical in everything except one factor; the difference is the effect of this factor

A process

switched on or off

Emissions

reduced, or one source removed: policy scenarios

Input data

another reanalysis, another land use

Model physics

another boundary-layer or radiation scheme

- Change only one thing at a time, and keep everything else identical
- Decide in advance what you will compare

The Experiment: CP1 and CP2

The same in both runs

domain (1 km) · meteorological input · BC emissions · physics schemes · January and July 2023

only one difference

CP1 — no interaction

WRF → CHIMERE only
BC has no effect on radiation

CP2 — online exchange

WRF <-> CHIMERE
aerosol optical properties sent to WRF
at every physical time step (10 min)

Everything that differs between the results is caused by the effect of black carbon on radiation

Design as in Tursumbayeva et al. (2026), Meteorological Applications, 33, e70183

What Is Compared: Radiative Metrics

Sunlight at the surface

$\Delta SW\downarrow = SW\downarrow(CP2) - SW\downarrow(CP1)$

How much less solar radiation reaches the ground

Net shortwave flux

$F = SW\downarrow - SW\uparrow$

At the top of the atmosphere (TOA) and at the surface (BOA)

Direct radiative effect

$DRE = F(CP2) - F(CP1)$

At each level, daytime, clear sky

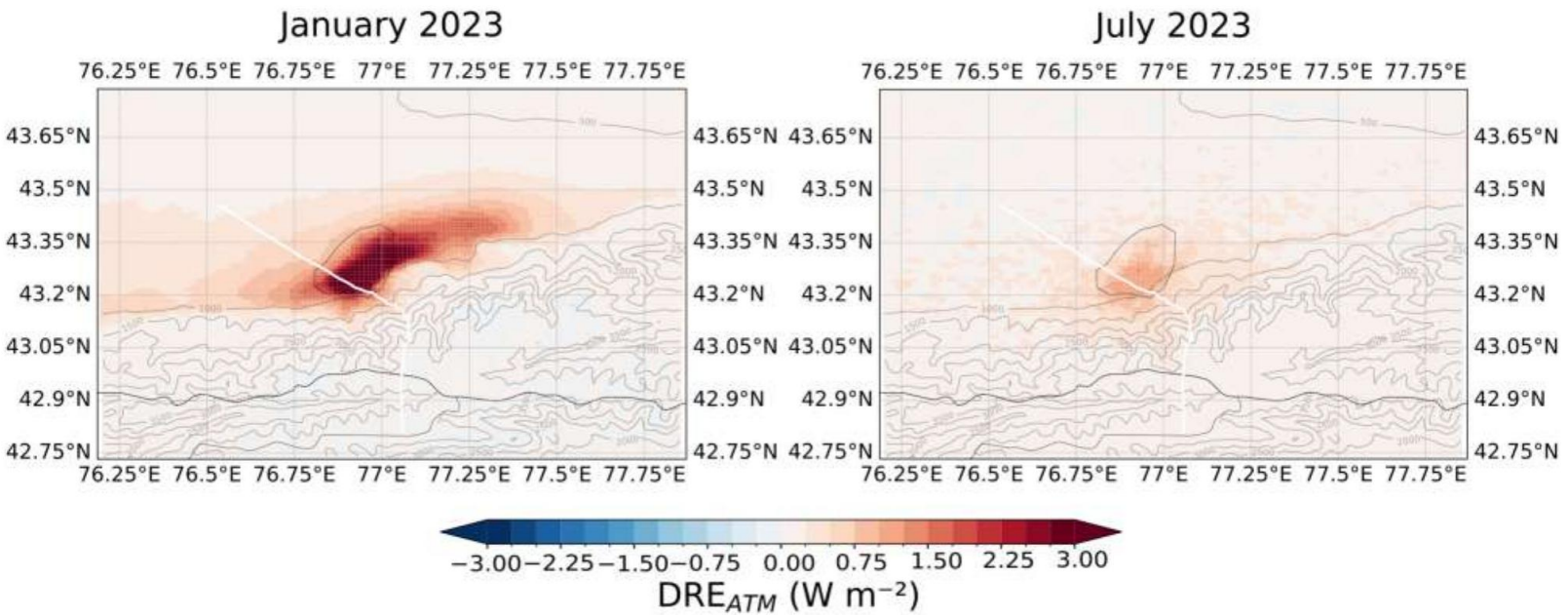
Effect within the atmosphere

$DRE_ATM = DRE_TOA - DRE_BOA$

The energy absorbed by the air

Definitions follow Equations 6–10 of Tursumbayeva et al. (2026), Meteorological Applications, 33, e70183

Result 1: Where Black Carbon Warms the Air

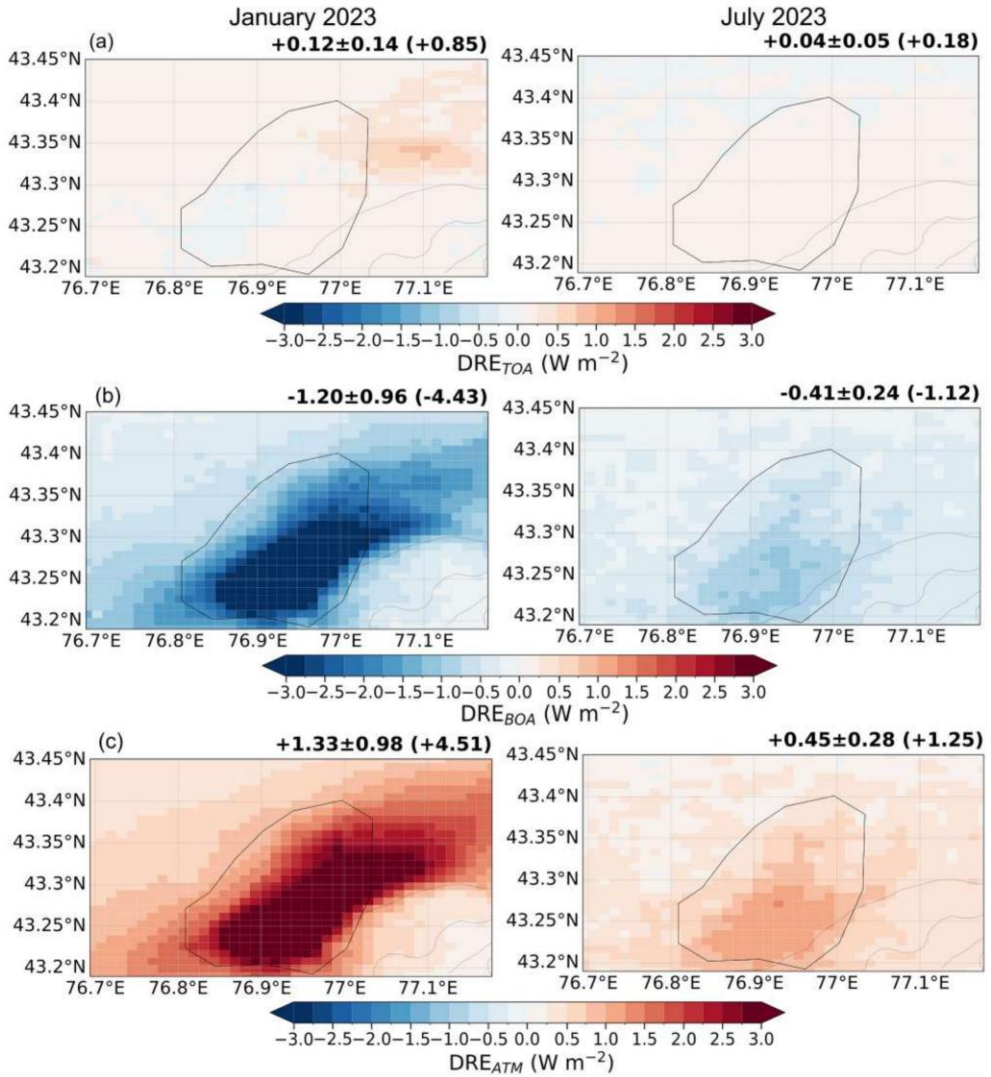


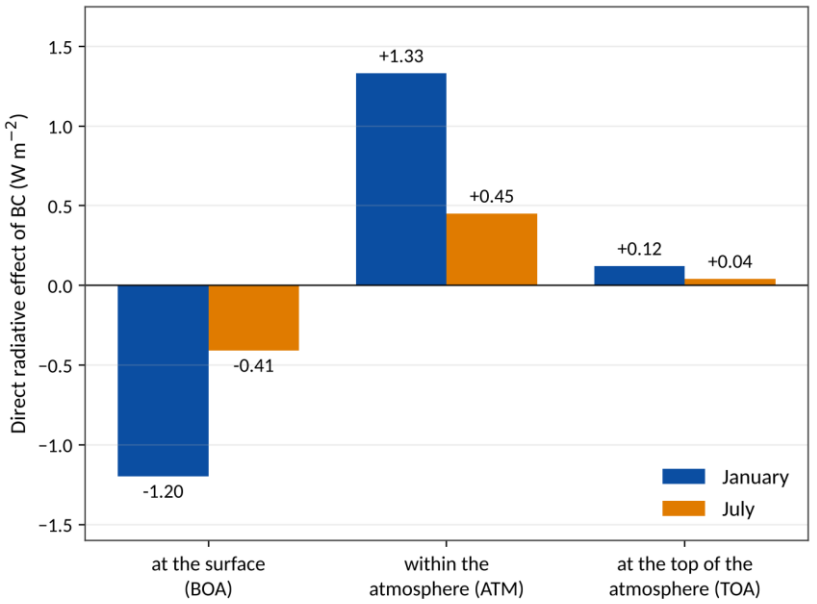
DRE within the atmosphere, CP2 − CP1. Source: Tursumbayeva et al. (2026), Meteorological Applications, 33, e70183

- Positive over the Almaty basin
- January: up to +4.5 W m^{-2}, over the city and along the foothills
- July: up to about +1.25 W m^{-2}
- In July it extends south, towards the mountains

The map of the effect follows the map of black carbon: basin in winter, valleys in summer

Result 2: The Three Radiative Effects



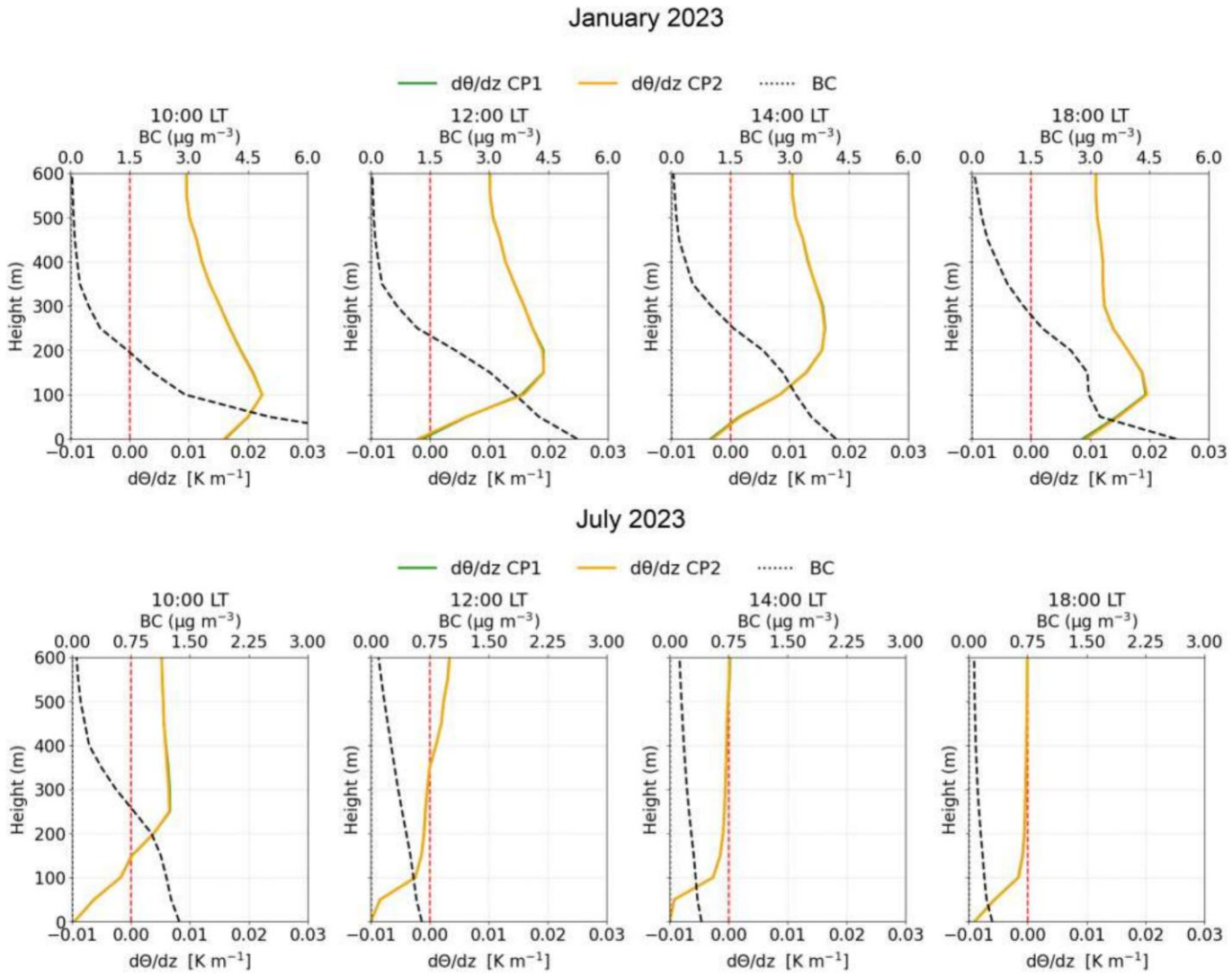


- Surface: −1.20 (down to −4.4)
- Atmosphere: +1.33
- Top: +0.12
- July: about 3 times smaller
- A lower bound: BC without coating

Values in W m^{-2}, mean over the urban area, January unless stated

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

Result 3: Did the Stability Change?



- Solid lines: dθ/dz in CP1 and in CP2
- They coincide: the difference is below 2 % in the lowest 200 m
- The radiative effect of about 1 W m^{-2} is too small

The loop is not closed

The strong, persistent inversion controls the boundary layer

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

How to Read a Sensitivity Result

Effect or noise?

Compare the difference with the natural variability

Conditions

Valid for January and July 2023; spring and autumn may differ

Simplifications

No coating of BC, one pollutant, one city

Next questions

BC on snow and glacier albedo; future emission scenarios

A negative result is also a result: here, meteorology controls the pollution, not the other way round

The Course in One Slide

1 WRF and its workflow	**2** Geogrid: domains and projections	**3** Ungrib and metgrid: input data	**4** The NetCDF format	**5** Mapping meteorological fields
6 Vertical structure	**7** Vertical cross-sections	**8** Model validation	**9** CHIMERE: air quality	**10** Interactions and sensitivity

A model is a laboratory for asking questions about the atmosphere

Thank you for your attention!

Conclusion

Key points

1. Meteorology controls pollution through wind, boundary-layer height, stability and precipitation; this explains most of its variability.
2. In winter black carbon accumulates in the Almaty basin under strong inversions; in summer the valley wind carries it up to about 4000 m.
3. Black carbon absorbs sunlight: it warms the atmosphere and reduces the radiation that reaches the surface.
4. A sensitivity analysis compares two runs that differ in one factor only; the difference is the effect of that factor.
5. In Almaty the direct effect is about 1 W m^{-2} in January and changes the stability by less than 2 %: the feedback loop is not closed.
6. A negative result is also a result, valid for the conditions and simplifications of the experiment.

Self-Check Questions

1. Through which meteorological factors does the weather control pollution?
2. Why is pollution in Almaty highest in winter?
3. How does black carbon change the radiation at the surface and within the atmosphere?
4. What is a sensitivity analysis, and what is its main rule?
5. What is the only difference between the runs CP1 and CP2?
6. Why did black carbon not change the stability noticeably in Almaty, and what limits this conclusion?

References

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