An intra-urban nocturnal cooling rate model

ICUC9

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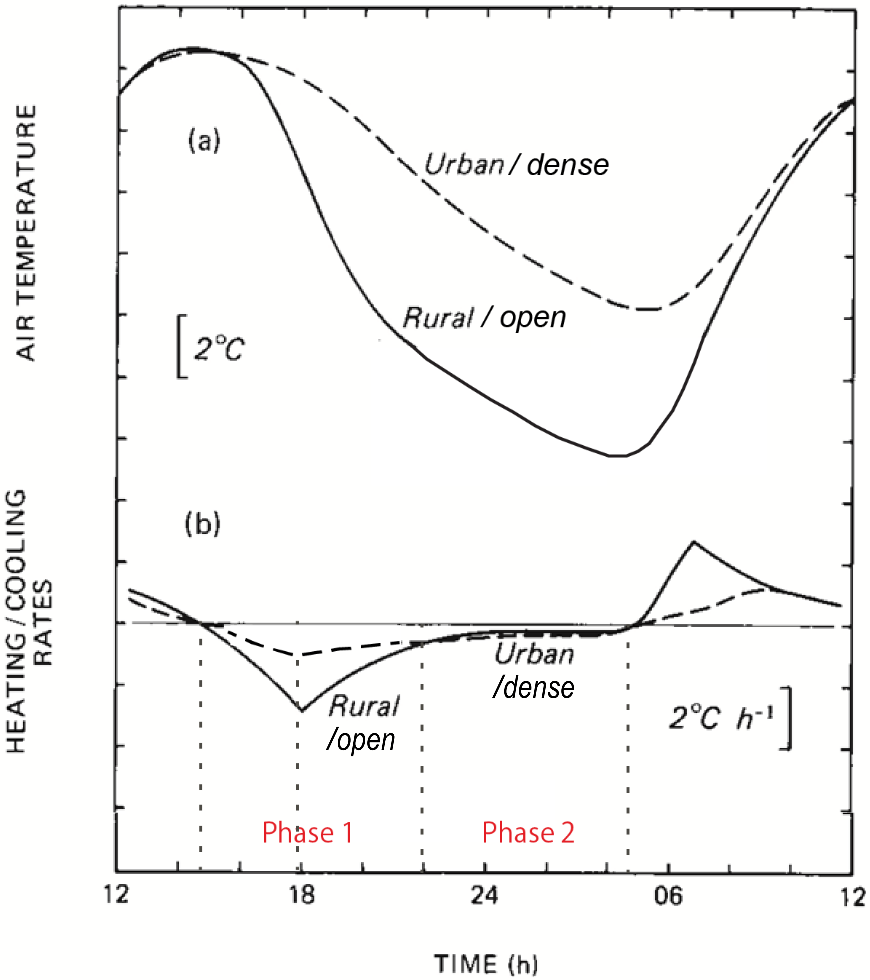
Two-phase nocturnal cooling



modified from Oke (1986)

Phase 1

- **site-dependent**
- most intensive cooling
- driven by sensible heat and longwave radiative divergence (Holmer et al. 2007)

Phase 2

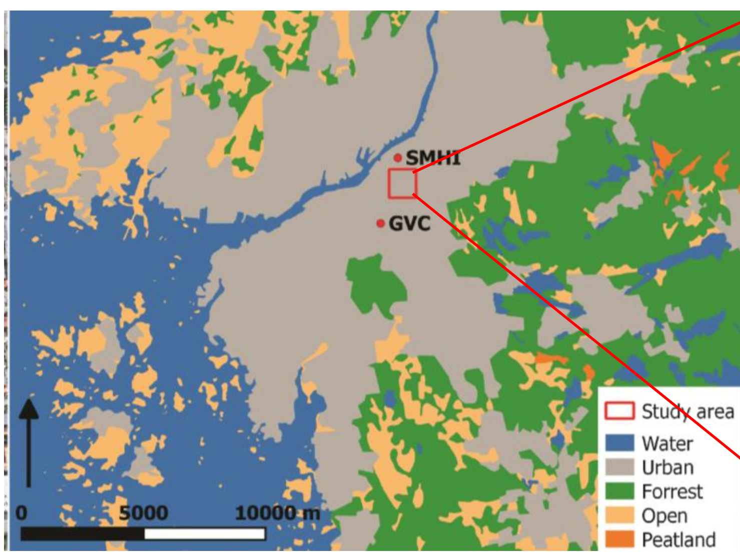
- **site-independent**
- gradually decreasing
- driven by raidative divergence in a capping inversion above the canonpy layer (Holmer et al. 2007)

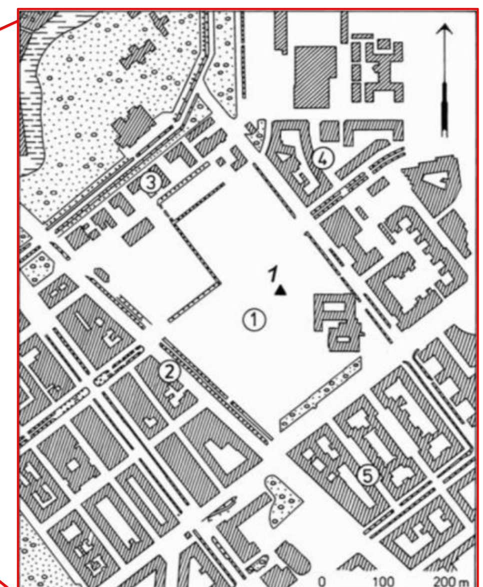
Objectives

To develop a nocturnal cooling rate model to simulate air temperature investigating the temporal development of nocturnal cooling and the relationship between cooling rates and meteorological variables and building density.

Dataset for model development

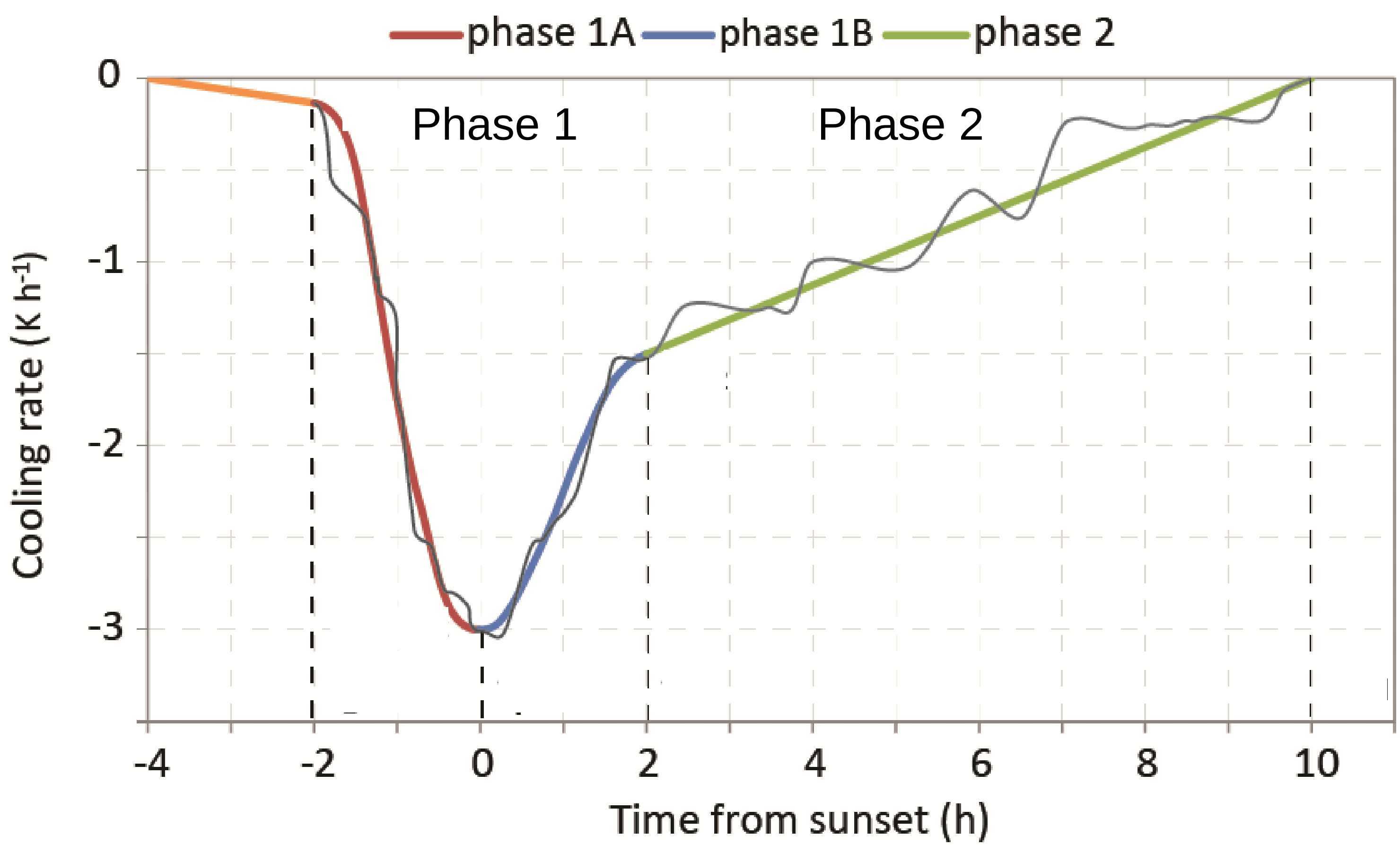
- Air temperature (2m) measured at **an open site** and **four built-up sites** with little vegetation in Gothenburg during May-Sep in 1999.
- U (10m), Ta, clearness of the sky (K↓, RH), from a nearby reference station (SMHI).
- Average sky view factor within a 25 m radius calculated using digital surface model and ArcMAP 10.1.





SVF
① 0.98
② 0.39
③ 0.40
④ 0.53
⑤ 0.39

A conceptual profile of nocturnal cooling rate



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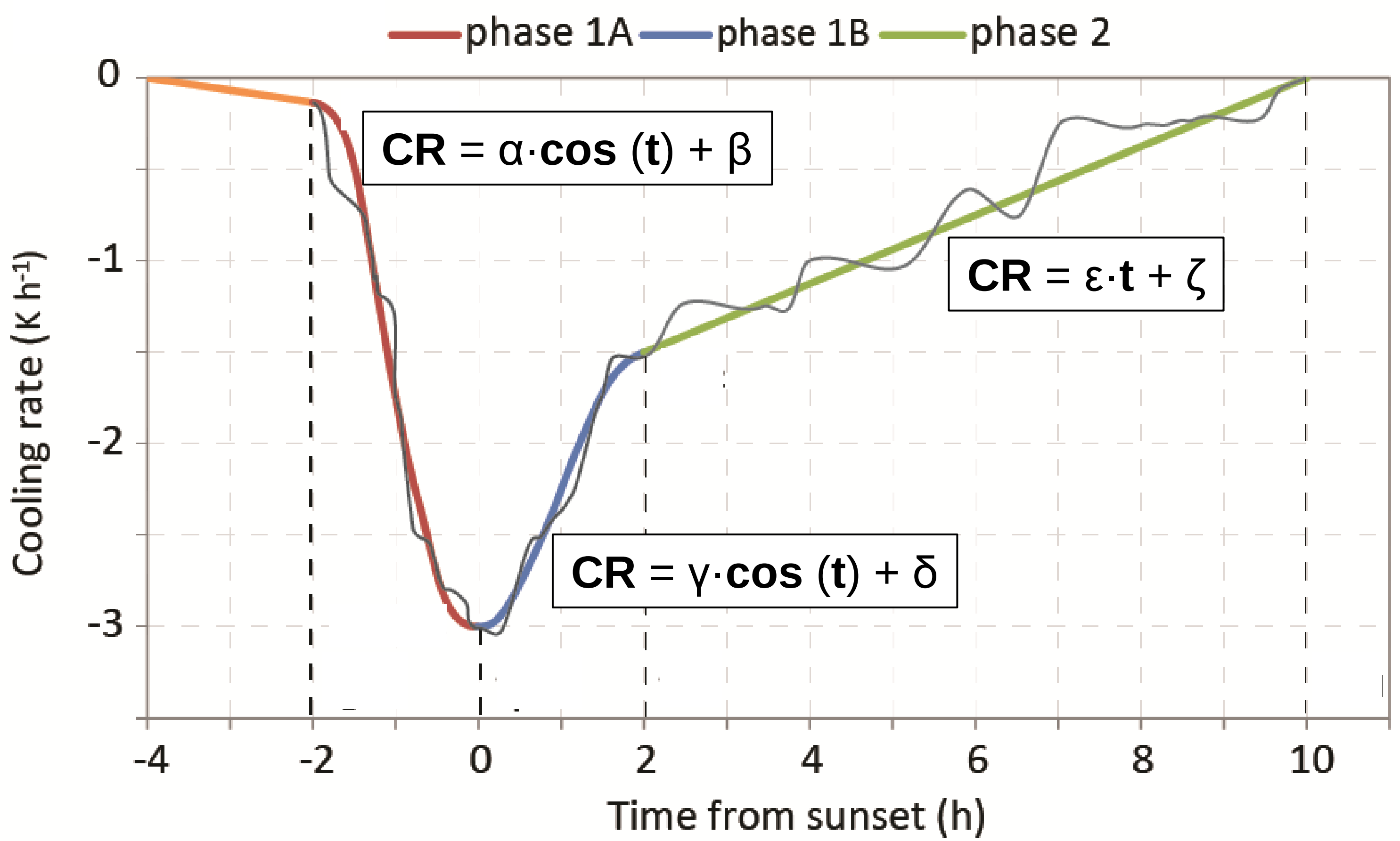

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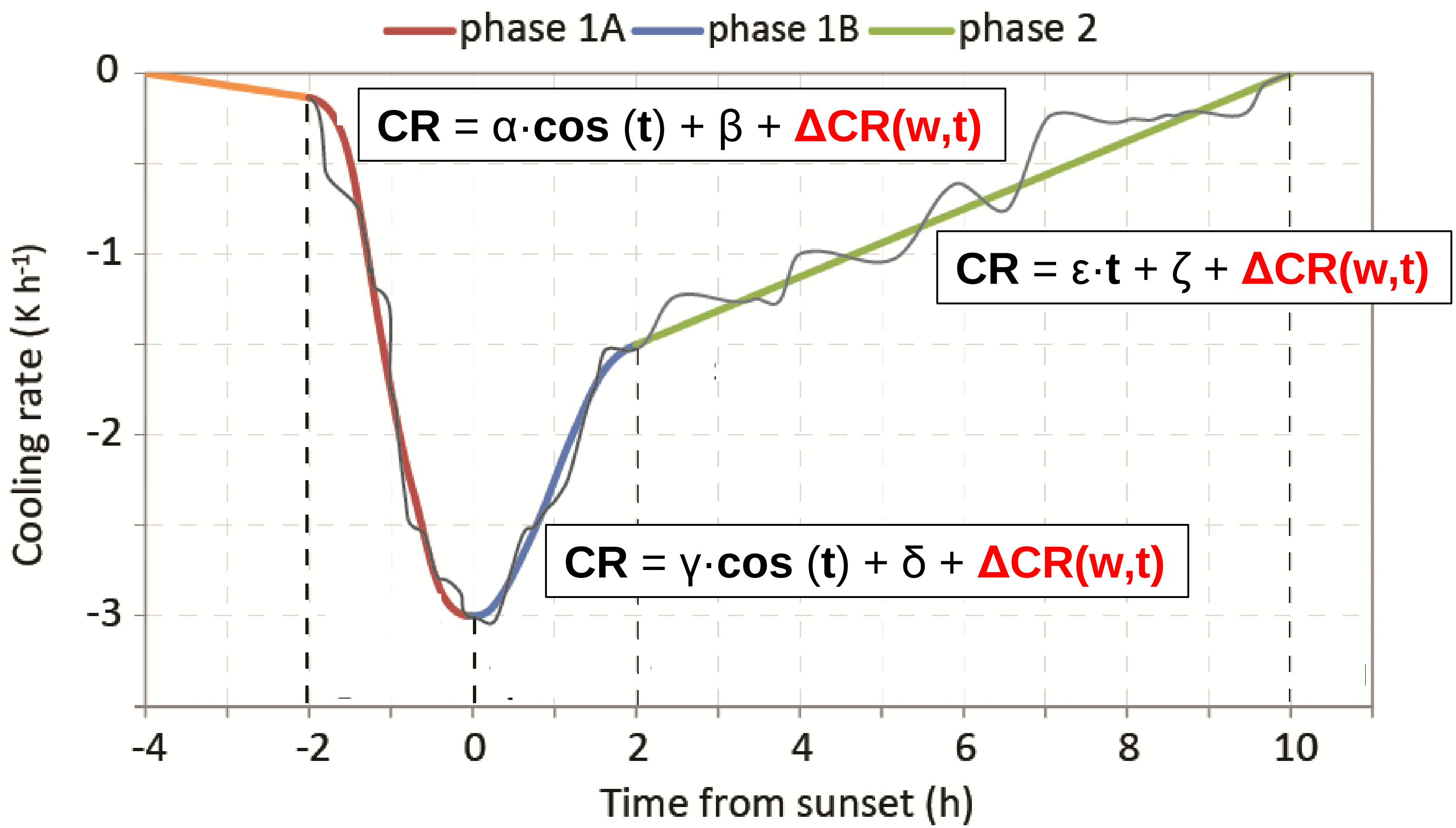

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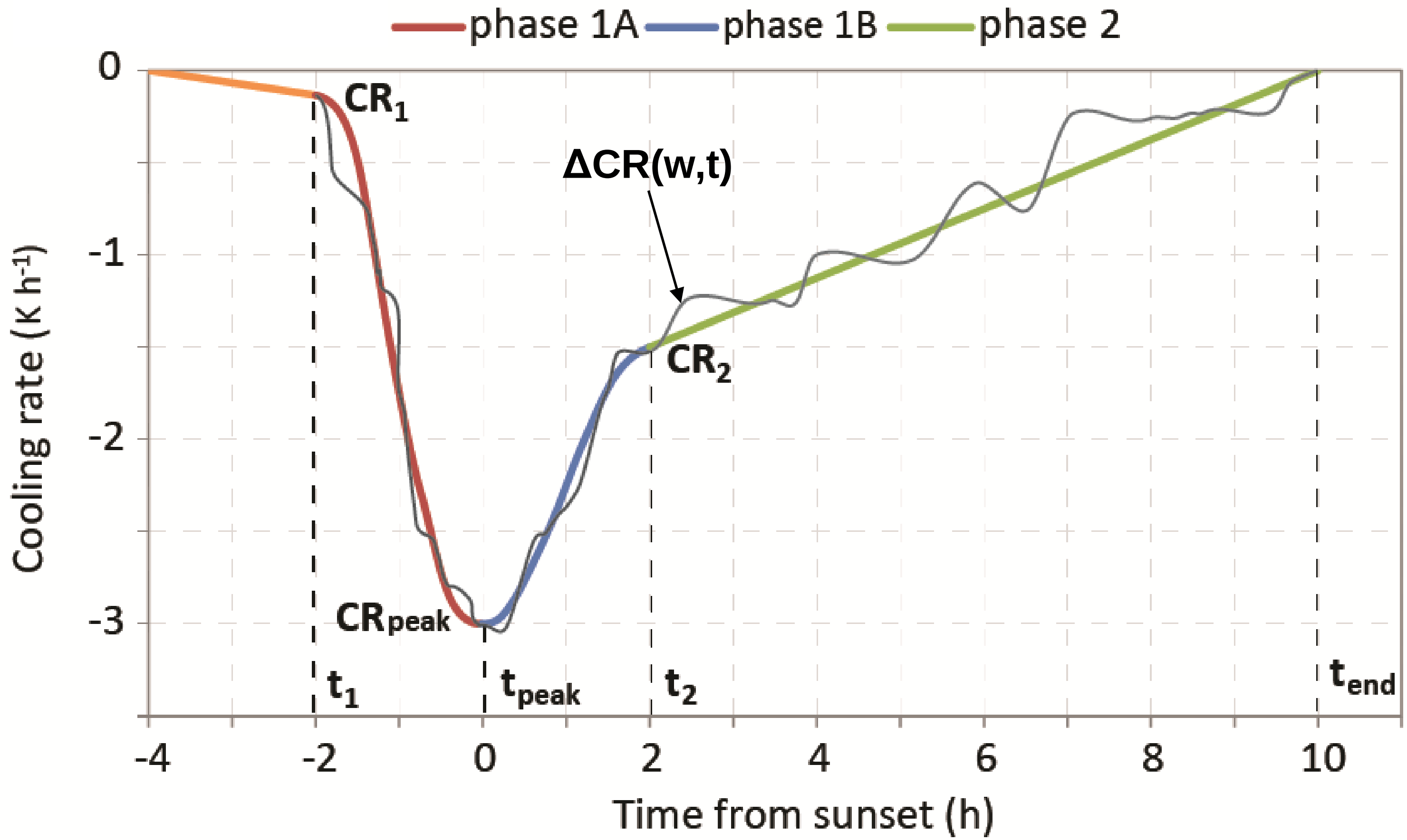
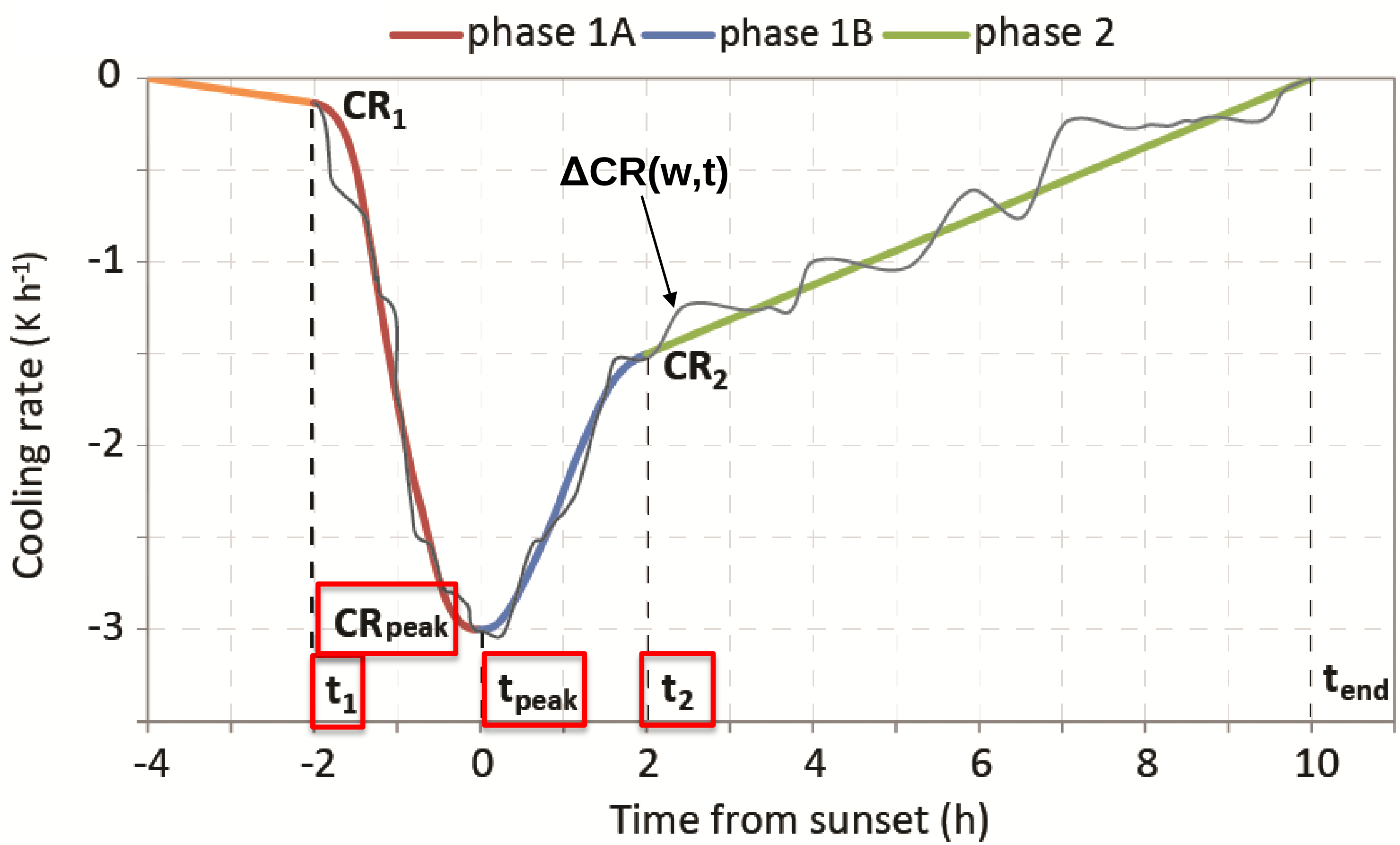
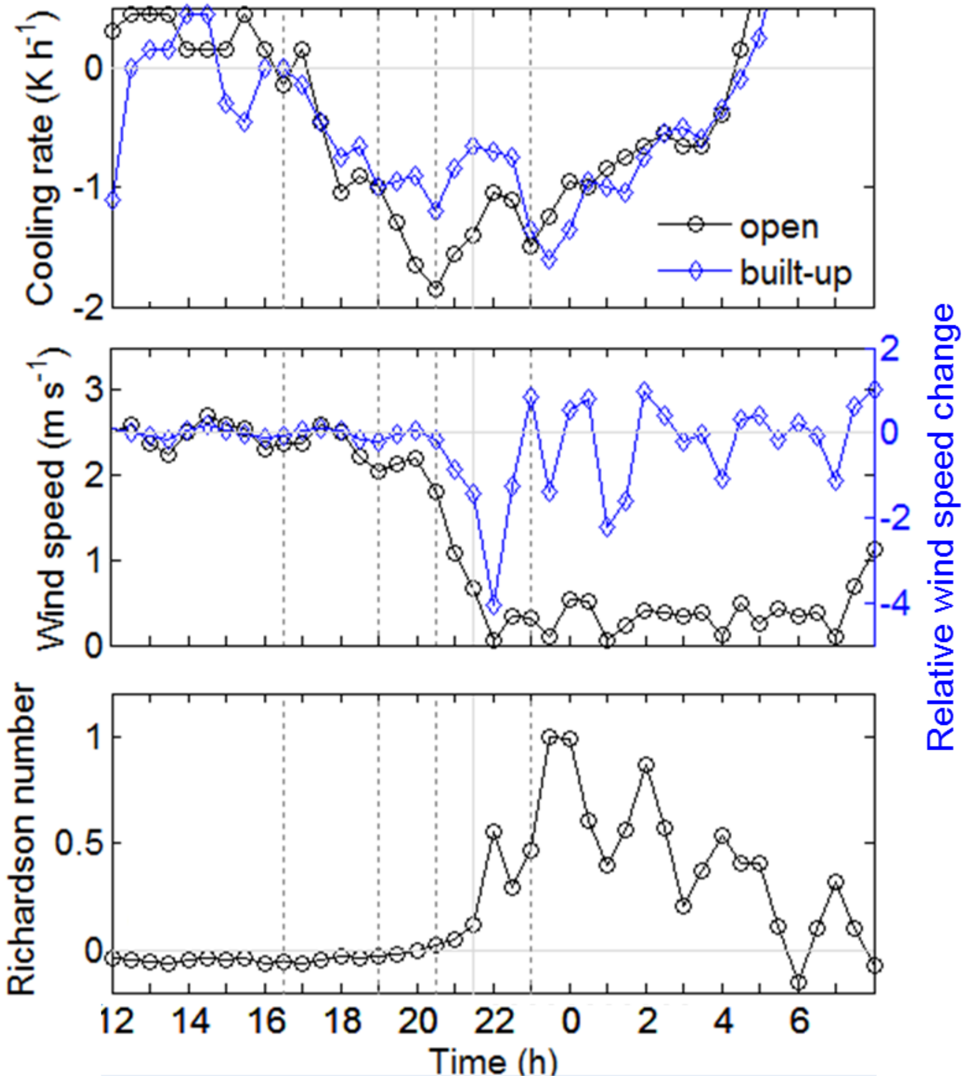


A conceptual profile of nocturnal cooling rate

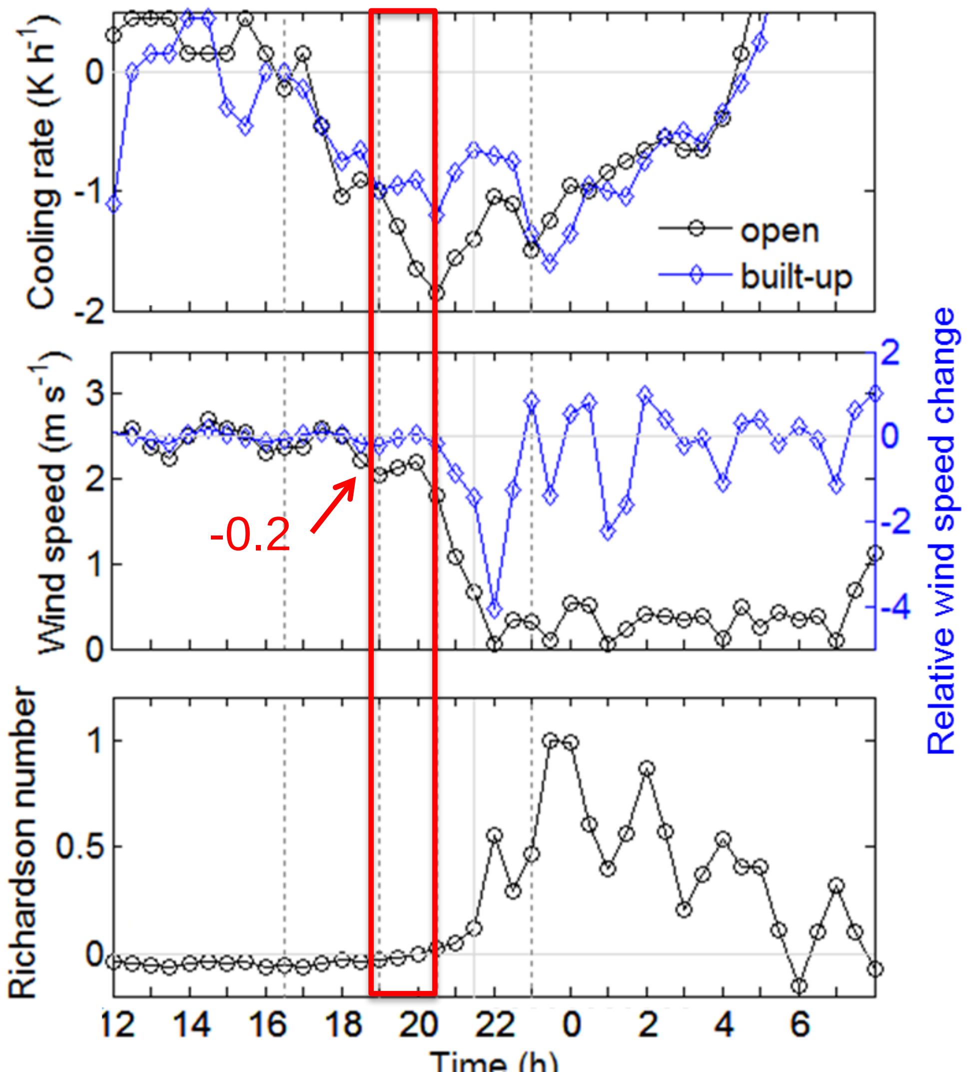


Onset of phase 1A,1B and 2 (t_1, t_{peak}, t_2)



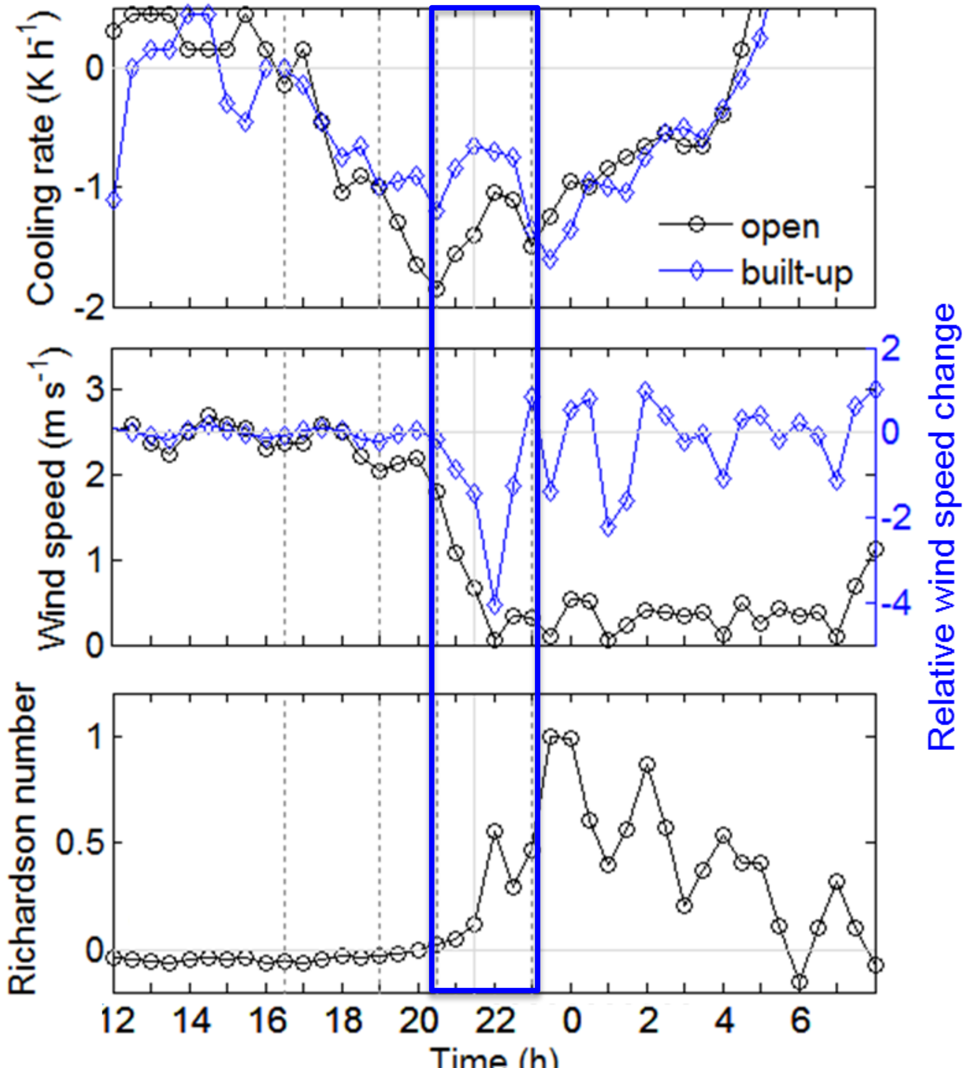
$$\frac{U_t - U_{t-1}}{(U_t + U_{t-1})}$$

Onset of phase 1A,1B and 2 (t_1, t_{peak}, t_2)



Phase 1A starts when relative wind speed change drops below -0.2.

Onset of phase 1A,1B and 2 (t_1, t_{peak}, t_2)

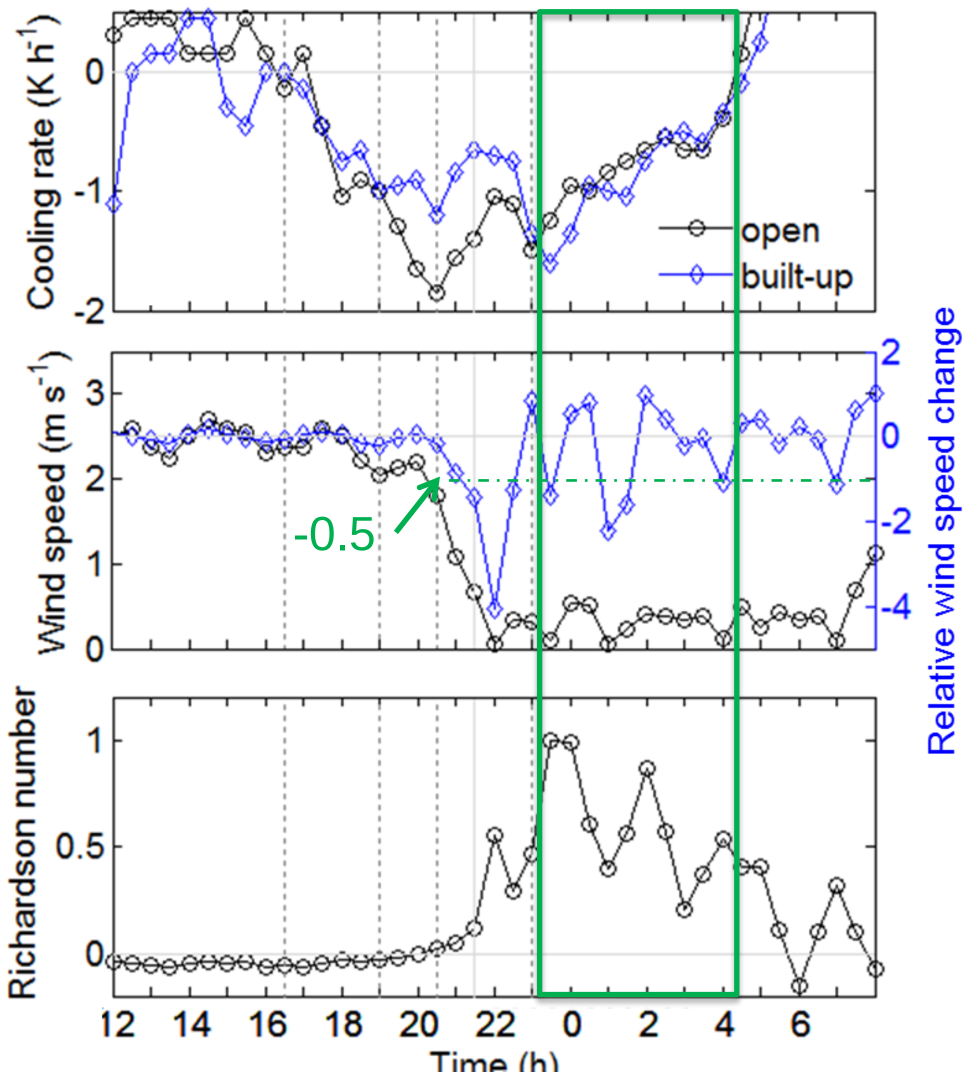


Phase 1A starts when relative wind speed change drops below -0.2.

Phase 1B occurs when the atmosphere turns from unstable to stable.

$$t_{peak} = t_1 + t_2$$

Onset of phase 1A,1B and 2 (t_1, t_{peak}, t_2)



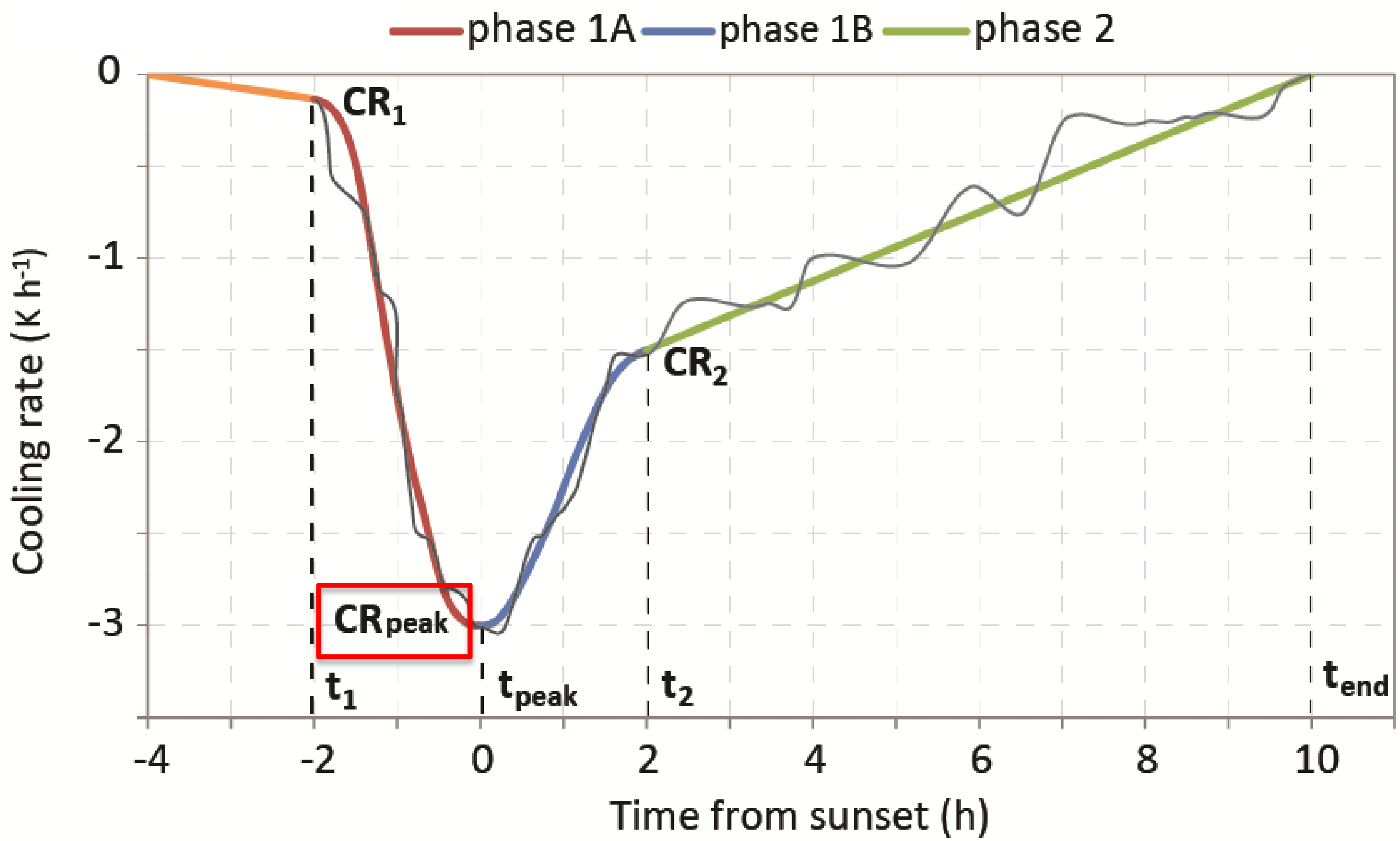
Phase 1A starts when relative wind speed change drops below -0.2.

Phase 1B occurs when the atmosphere turns from unstable to stable.

$$t_{peak} = t_1 + t_2$$

Phase 2 starts 1 hr after relative wind speed change drops below -0.5.

Determination of CR_{peak}



Determination of CR_{peak}

- clearness of the sky (CI)
- wind speed (U)
- maximum daily air temperature (T_{max})
- sky view factor (SVF)

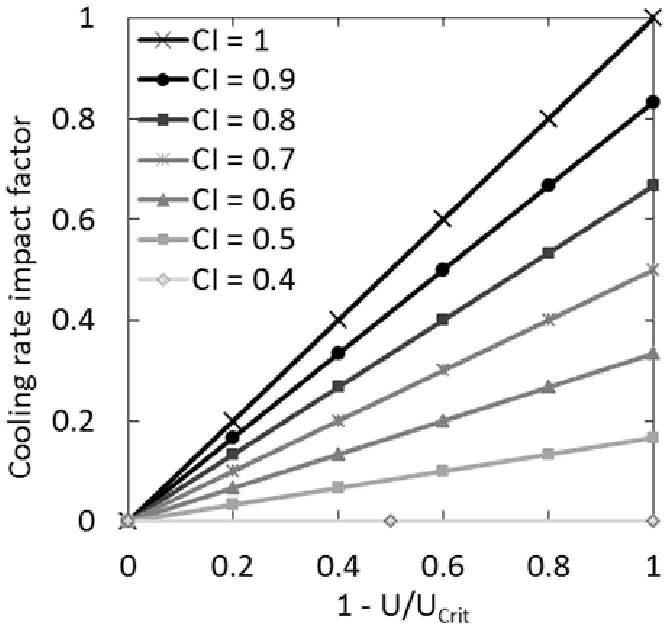
Cooling rate impact factor (CRIF)

$$CRIF = \left(1 - \frac{U}{U_{crit}}\right) \cdot \frac{(CI - CI_{min})}{(CI_{max} - CI_{min})}$$

$U_{crit} = 4$ m/s

$CI_{max} = 1$

$CI_{min} = 0.4$

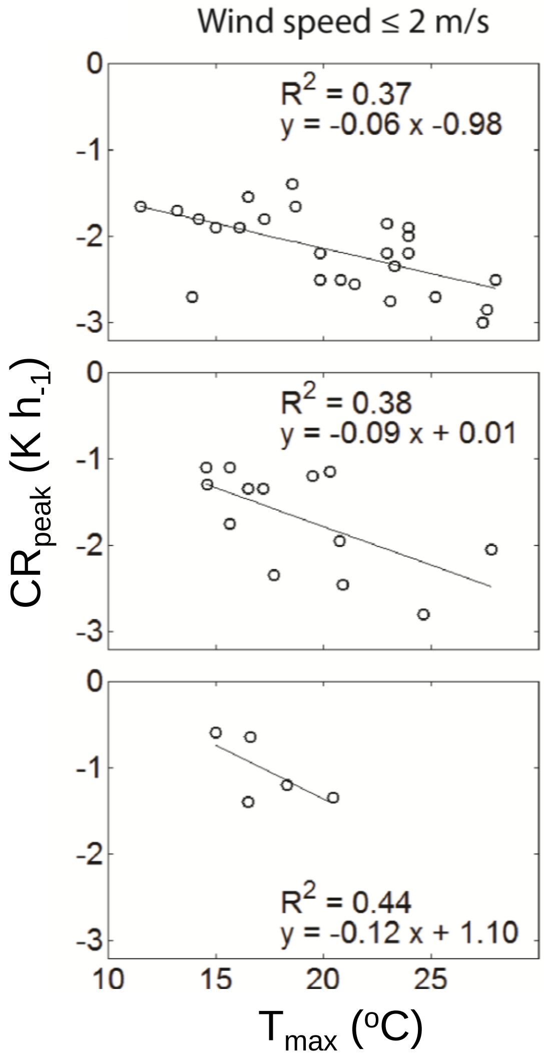


The relationship between CR_{peak} and T_{max}

clear
CRIF= 0.72

semi-cloudy
CRIF=0.48

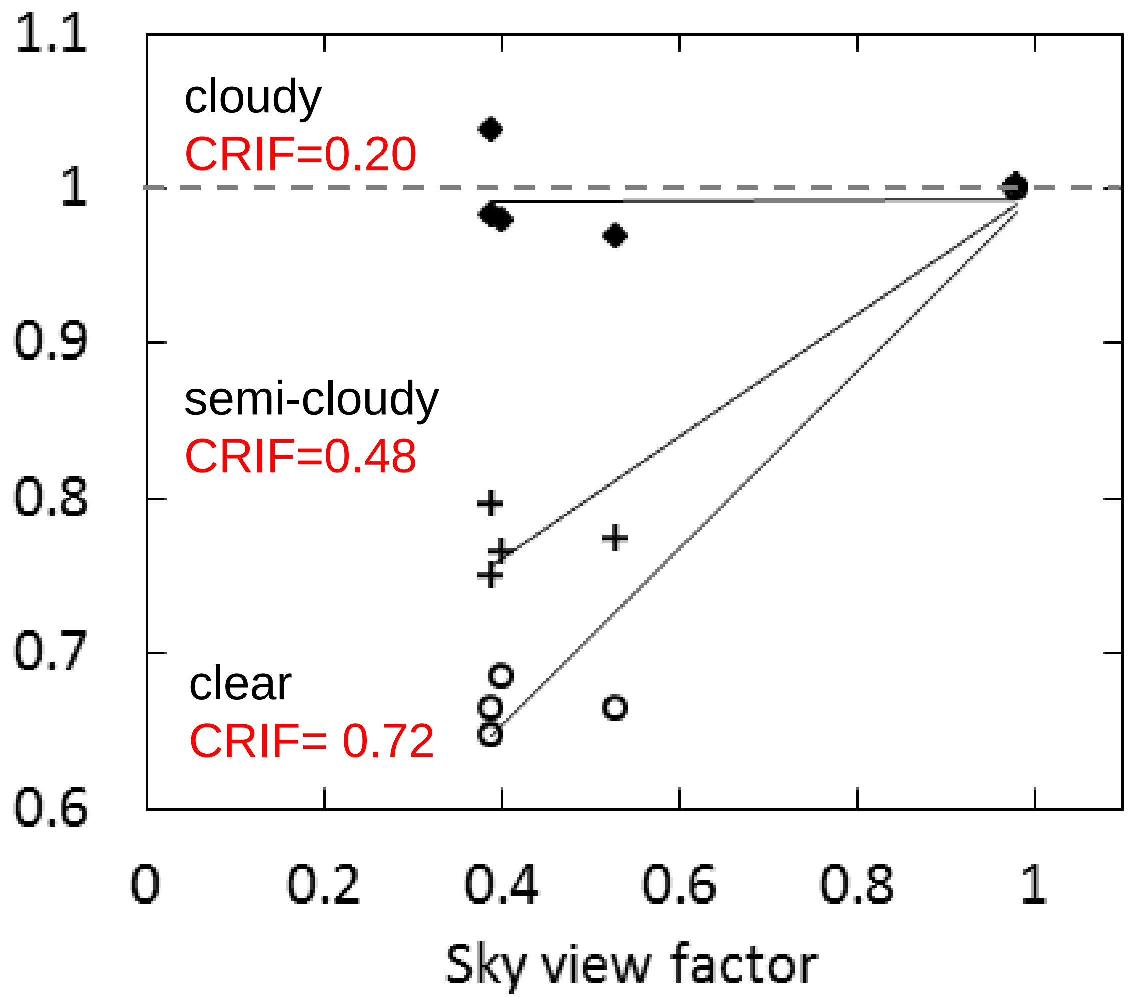
cloudy
CRIF=0.20



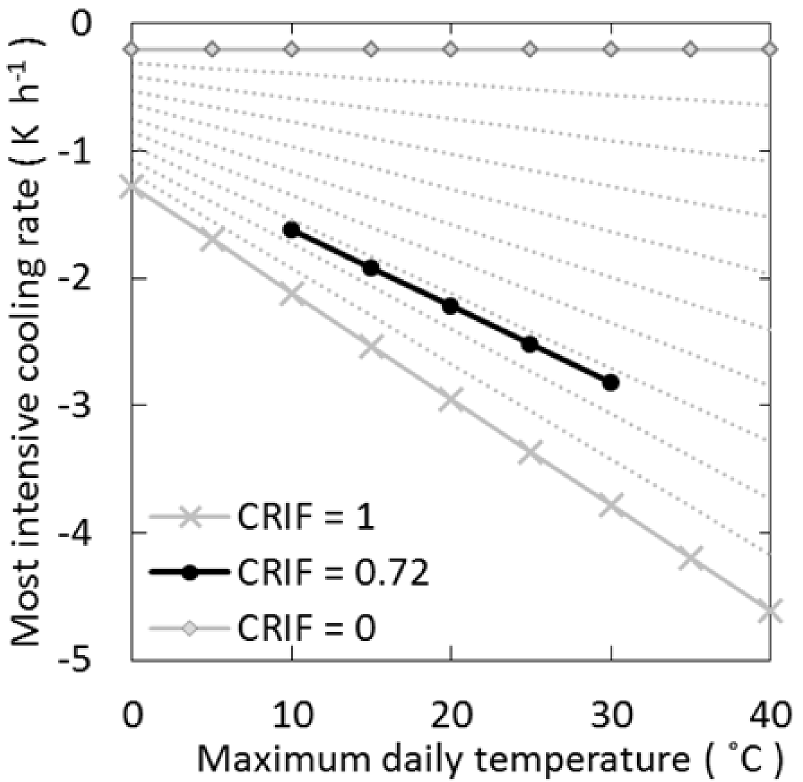
The impact of SVF on cooling rate

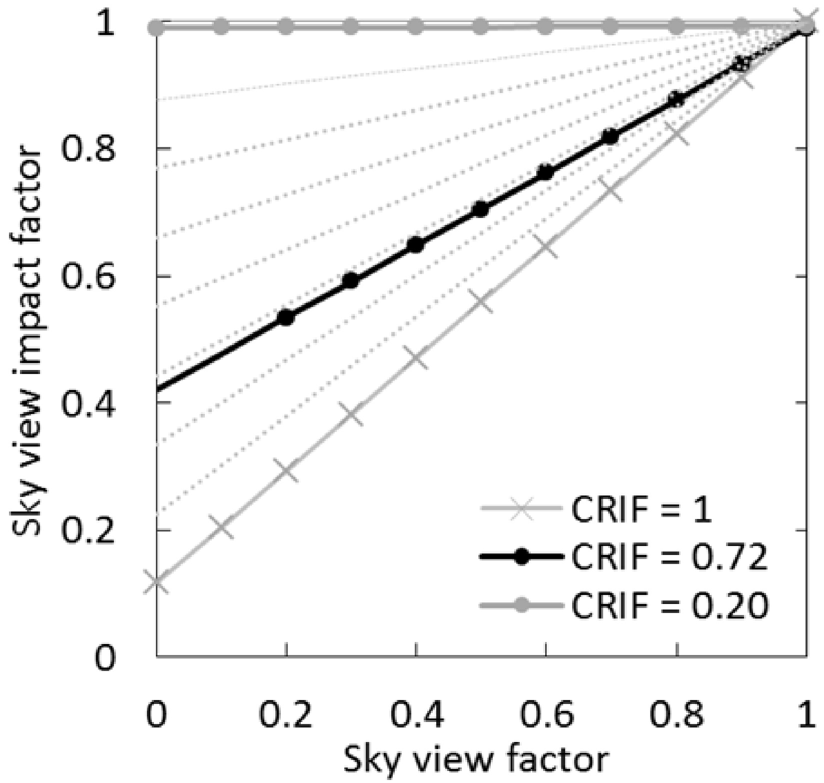
$$\frac{CR_{peak,built-up}}{CR_{peak,open}}$$

=Sky View Impact Factor (SVIF)



Determination of CR_{peak}





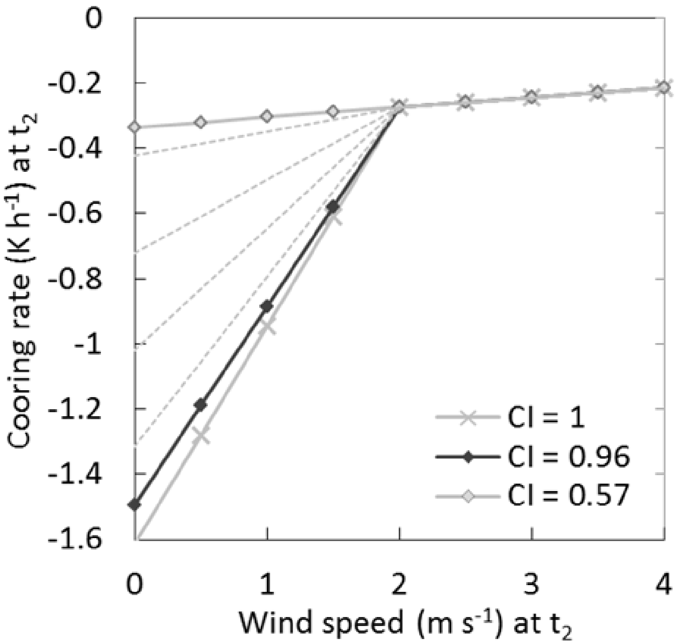
$$CR_{peak} = [-0.2 - 0.083 \cdot CRIF \cdot (T_{max} + 13)] \cdot SVIF$$

Determination of CR_2

$$CR_2 = CR_{2\_min} + \left(CR_{2\_clear} - CR_{2\_min}\right) \cdot \frac{CI - 0.57}{1 - 0.57}$$

$$CR_{2\_clear} = -1.6 + 0.67 \cdot U_2$$

$$CR_{2\_min} = -0.34 + 0.03 \cdot U_2$$



Impact of wind speed change

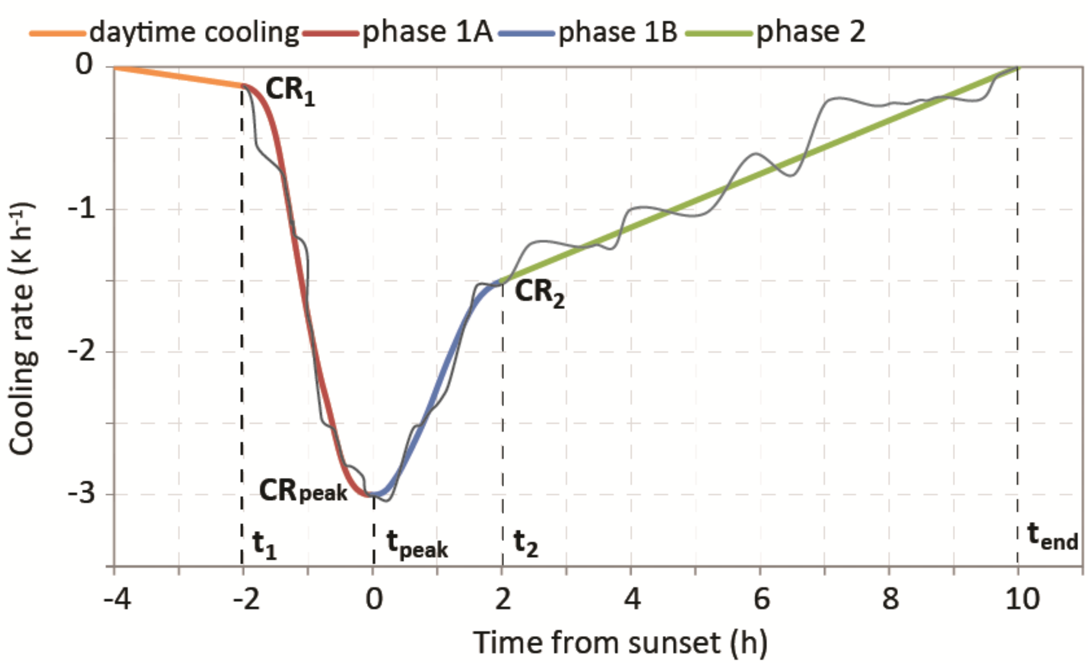
$$\Delta CR_w(t) = \begin{cases} -\alpha \cdot \left(U(t) - U_{ave,phasex}\right)^{1/3}, & if\ x = 1A \\ +\alpha \cdot \left(U(t) - U_{ave,phasex}\right)^{1/3}, & if\ x = 1B\ or\ 2 \end{cases}$$

Fundamental equations

Phase 1A $CR = \left(CR_1 - CR_{peak}\right) \cdot \left(\cos\left(f(t - t_1)\right) - 1\right)/2 + CR_1 + \Delta CR_w(t)$

Phase 1B $CR = \left(CR_2 - CR_{peak}\right) \cdot \left(\cos\left(f\left(t - t_{peak}\right)\right) + 1\right)/2 + CR_{peak} + \Delta CR_w(t)$

Phase 2 $CR = \frac{t_{end} - t}{t_{end} - t_2} CR_2 + \Delta CR_w(t)$



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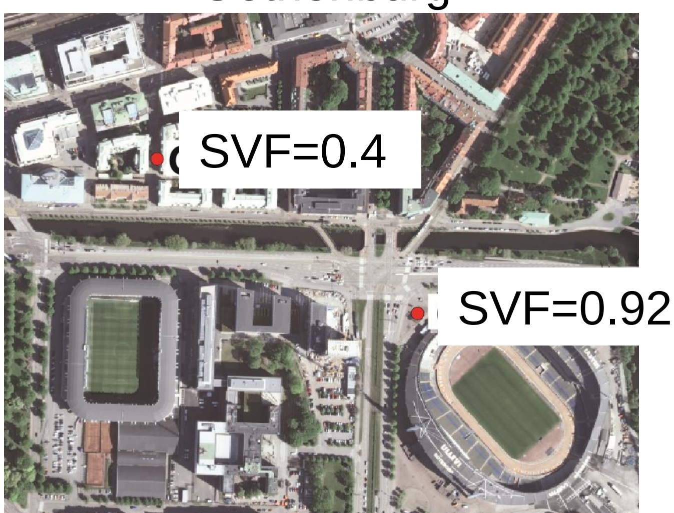
Model evaluation

Observational data from

- A open (SVF=0.92) site and a built-up (SVF=0.40) site in Gothenburg,Sweden
- A complex built-up (SVF=0.46) site in London, UK

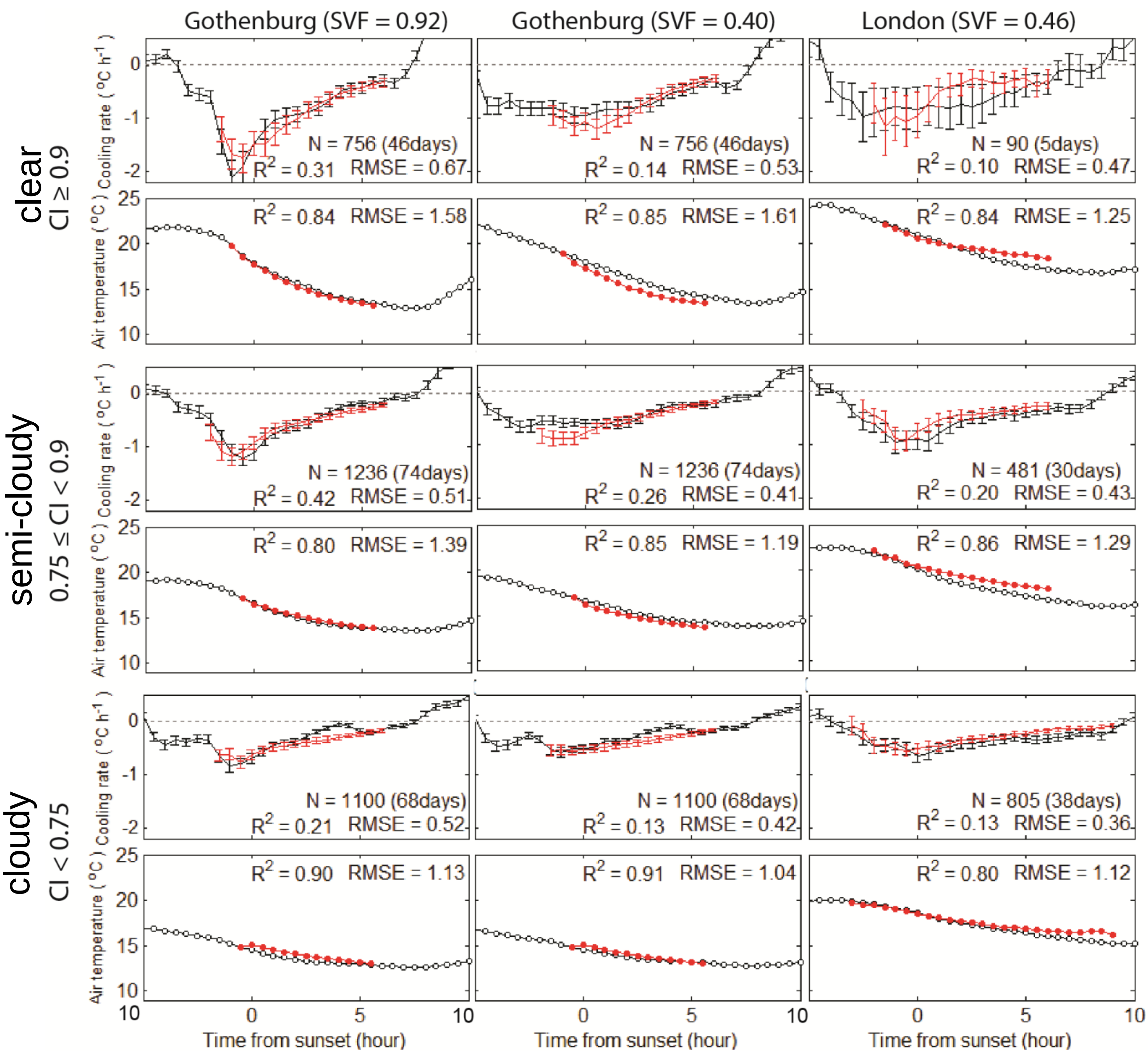
during May – Sep in 2012 and 2014. The sites have little vegetation.

Gothenburg



London

Model results



Summary

- **A intra-urban nocturnal cooling model** was developed based on the concept of two-phase cooling.
- The model successfully estimates cooling rate under **a wide range of weather (CI and U) condition** as well as at **sites of different building densities**.

Future work

- To be tested for other cities, e.g. lower latitudes and/or with very different site characteristics.
- To take into account the impact of anthropogenic heat and latent heat fluxes.
- To be used in climate application, e.g. human thermal comfort estimation.

Thank you for your attention.

Aknowledgement

- This project is financially supported by the Swedish Research Council Formas, the Swedish Energy Agency, the Swedish Environmental Protection Agency, the Swedish National Heritage Board and the Swedish Transport Administration.
- We appreciate Prof. Sue Grimmond, Dr. Simone Kotthaus, Mr. William Morrison and Ms. Janina Konarska for providing observational data.

Relevant research paper

- Onomura S, Homer B, Lindberg F and Thorsson S (2015) Urban nocturnal cooling rates: development and evaluation of the NOCRA Model. Manuscript.
- Konarska J, Homer B, Lindberg F and Thorsson S (2015) Influence of vegetation and building geometry on the spatial variations of air temperature and cooling rates in a high latitude city. In Review, Int J Climatol

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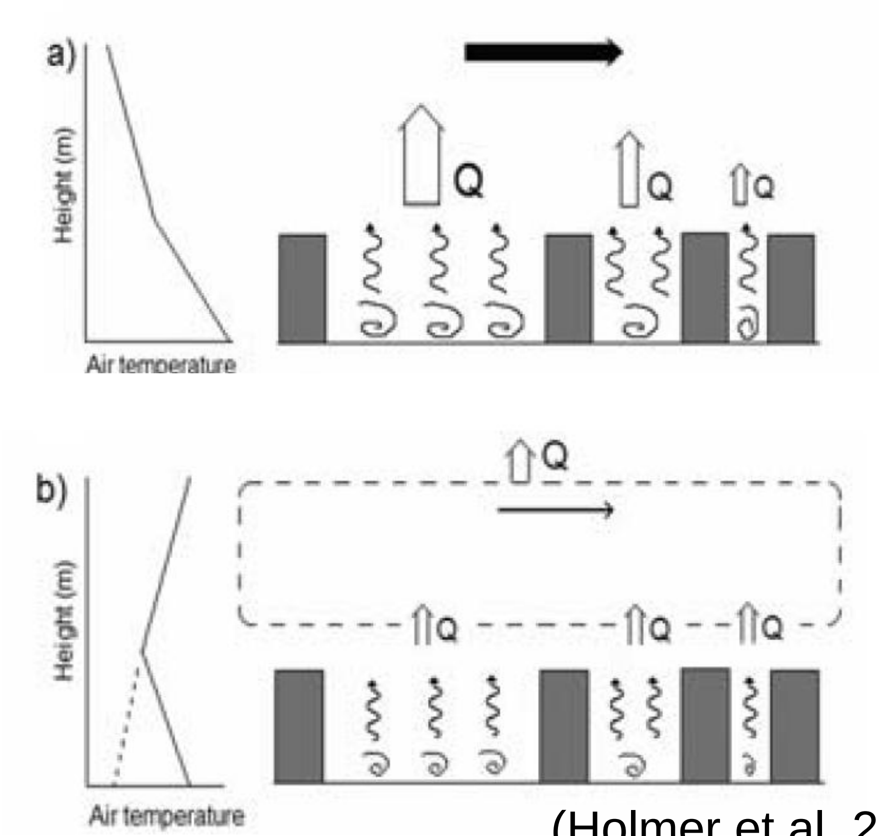
Two-phase nocturnal cooling



(Holmer et al. 2007)

- Two-phase cooling (ex. Chow and Oke 2006)

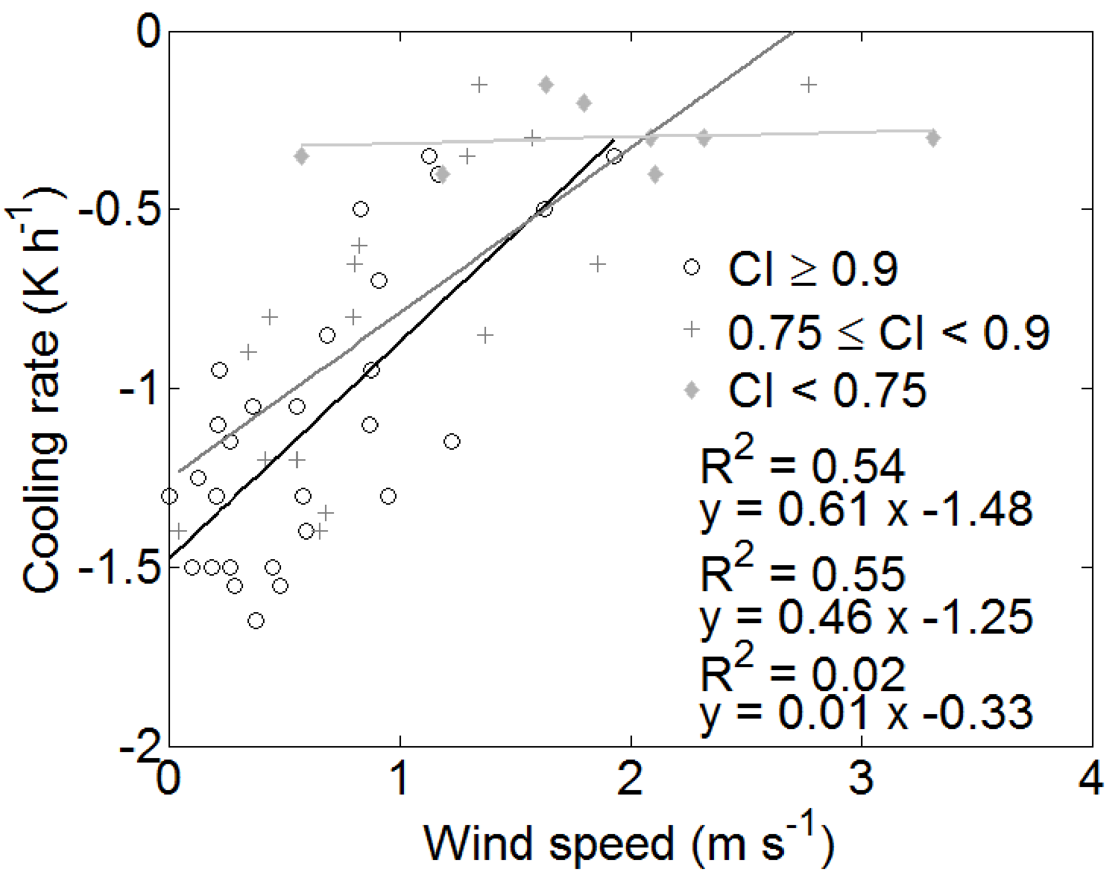
  Phase 1 : site-dependent
  most intensive cooling

  Radiative divergence
  Sensible heat flux

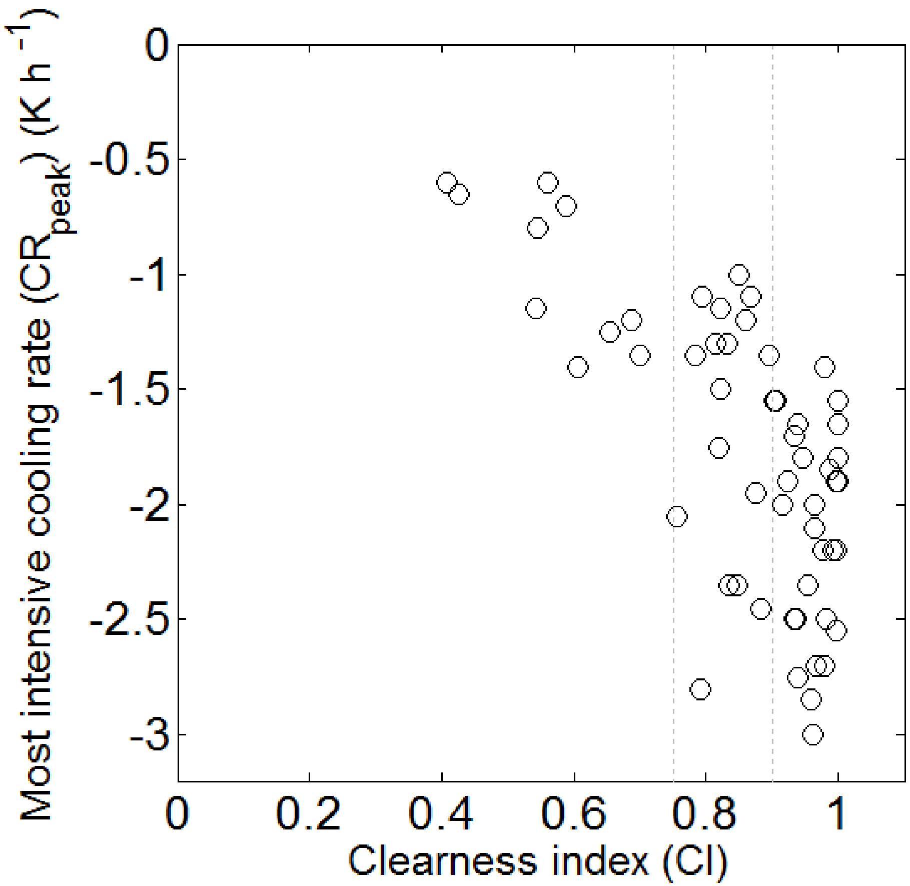
  Phase 2 : site-independent
  gradually decreasing

  Radiative divergence
  in a capping inversion
  above the canopy layer

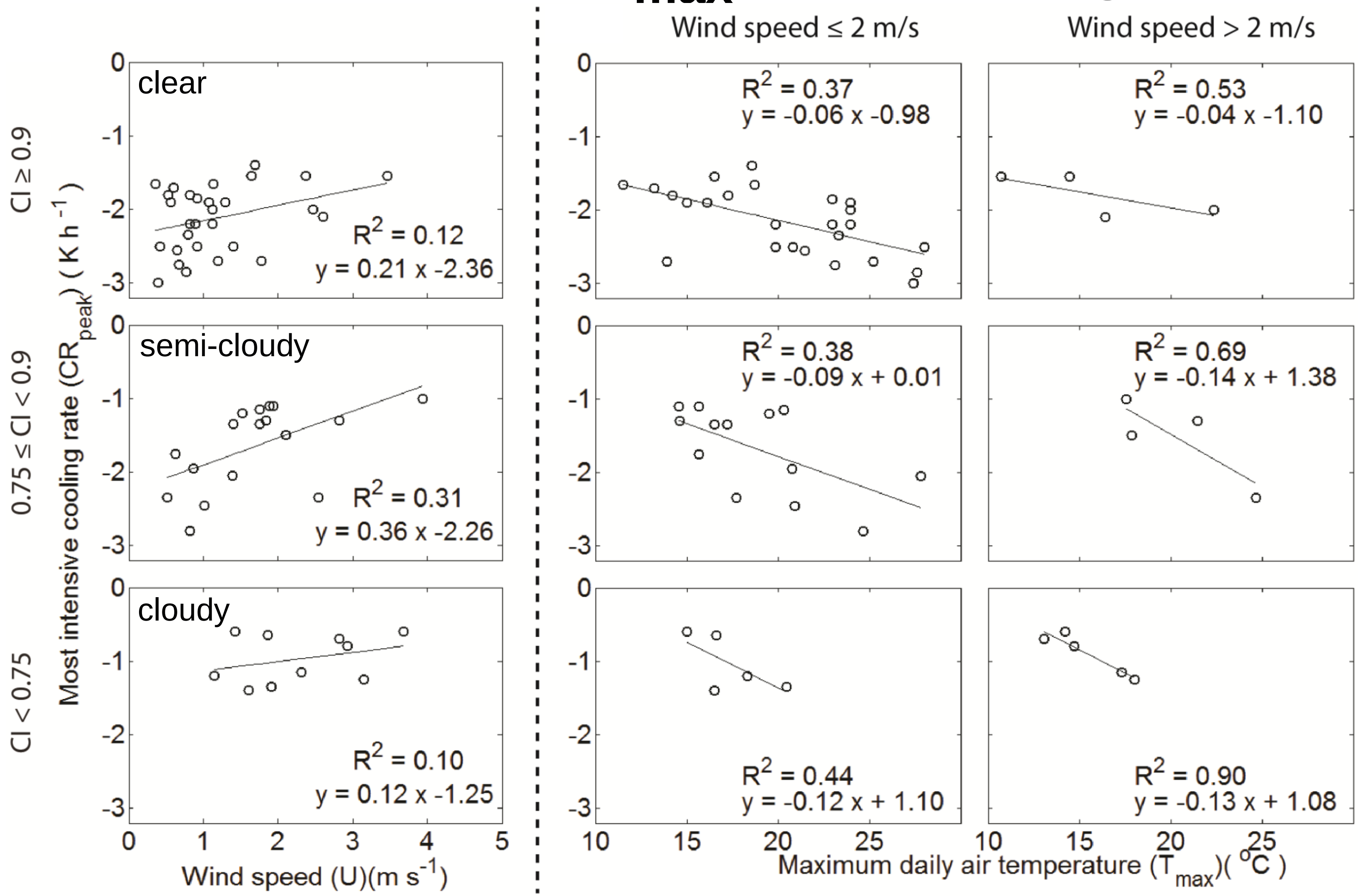
Cooling rate (CR_2) at the start of phase 2



Impact of cloudiness on CR_{peak}



Impact of U and T_{max} on cooling rate



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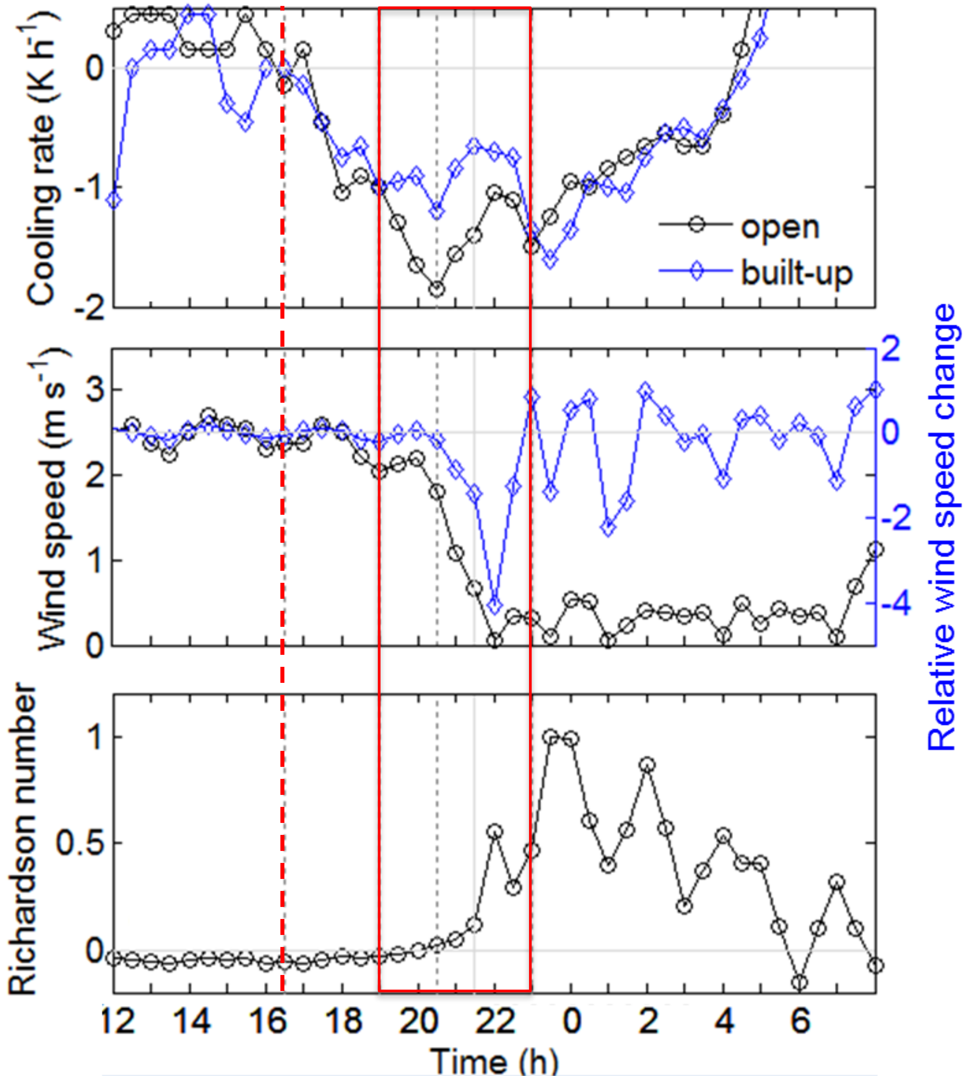

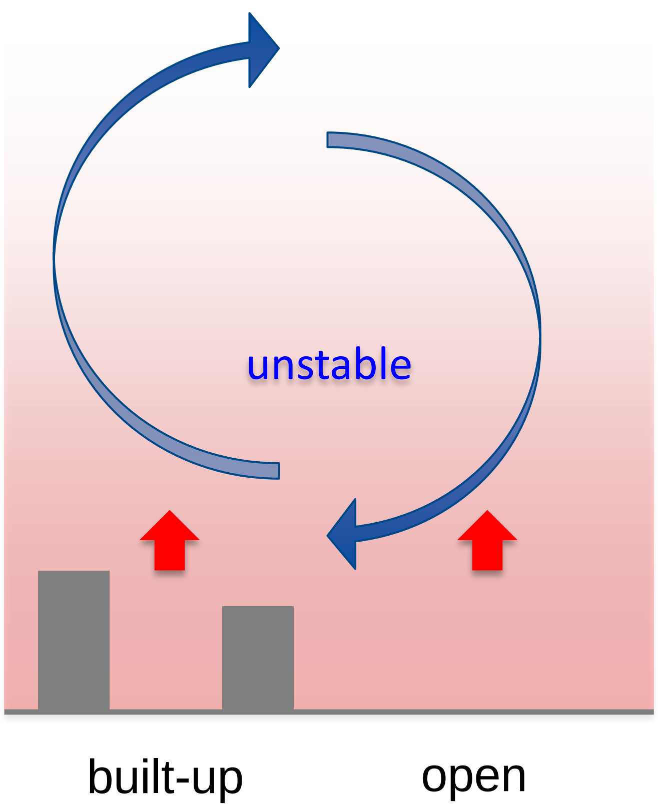

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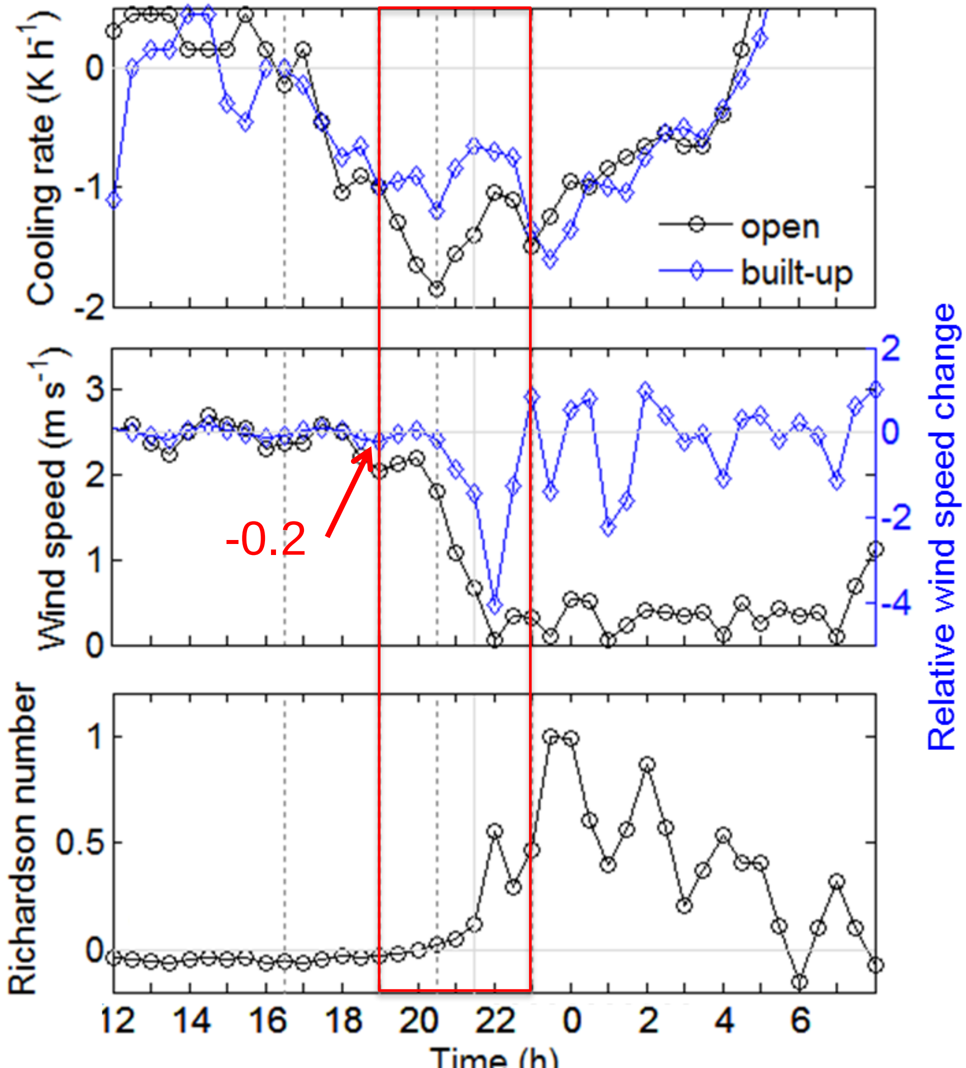

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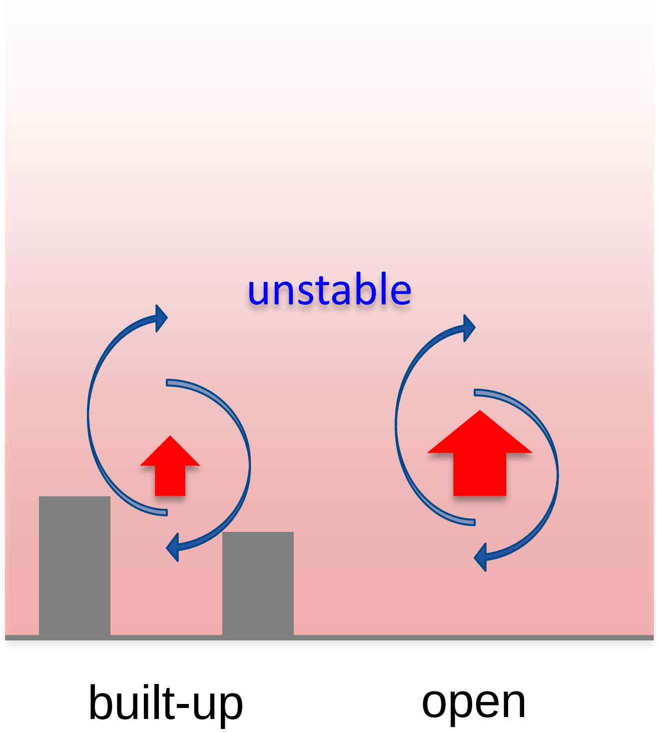
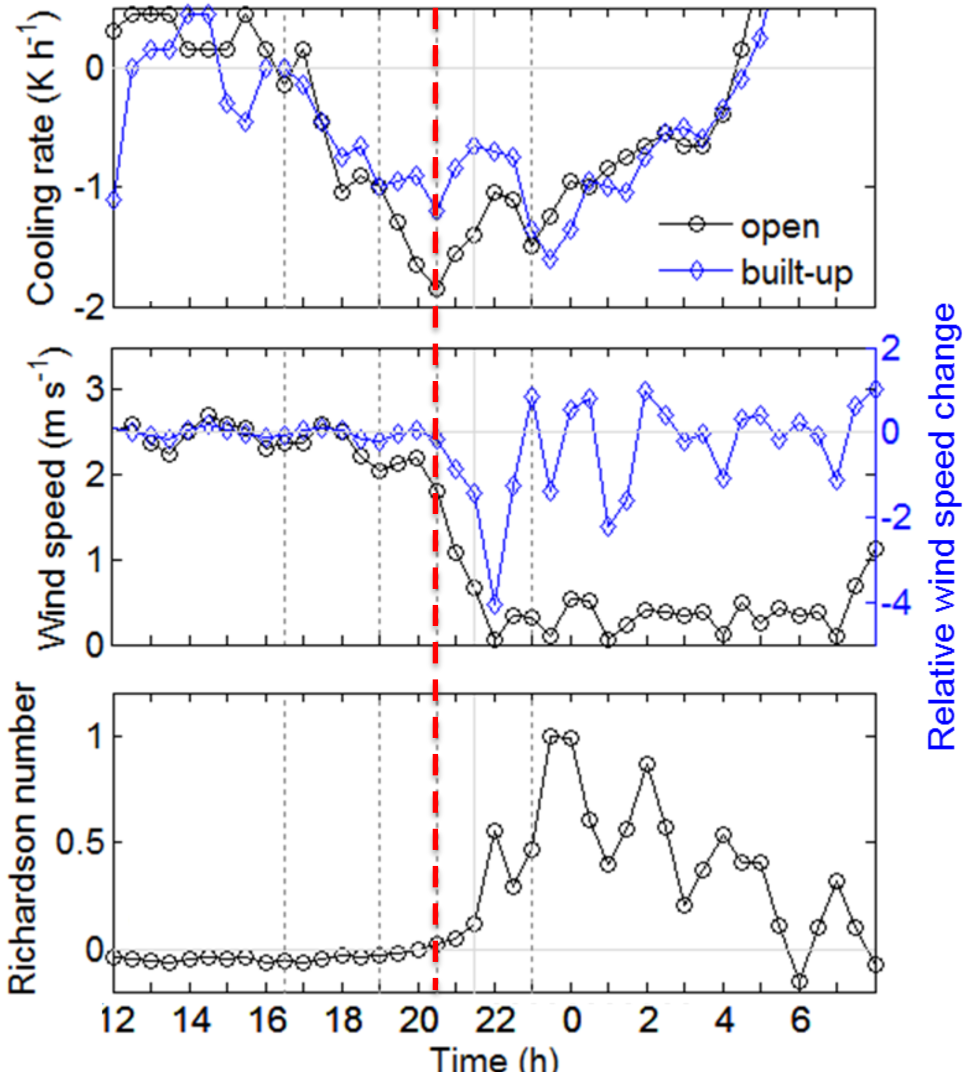


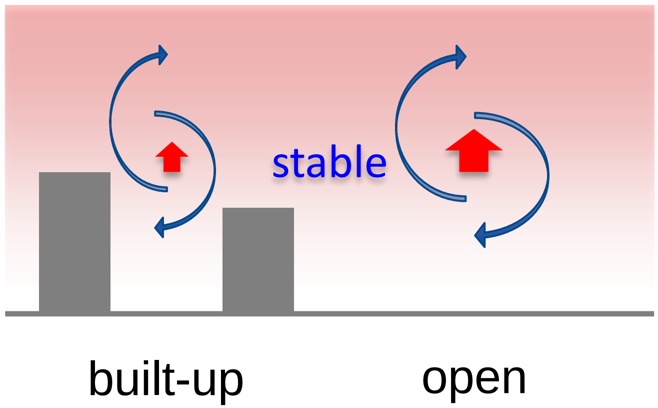
Onset of phase 1A,1B and 2 (t_1, t_{peak}, t_2)



Phase 1 starts when relative wind speed change drops below -0.2.

Most intensive cooling occurs when the atmosphere turns from unstable to stable.

$t_{peak} = (t_1 + t_2)/2$



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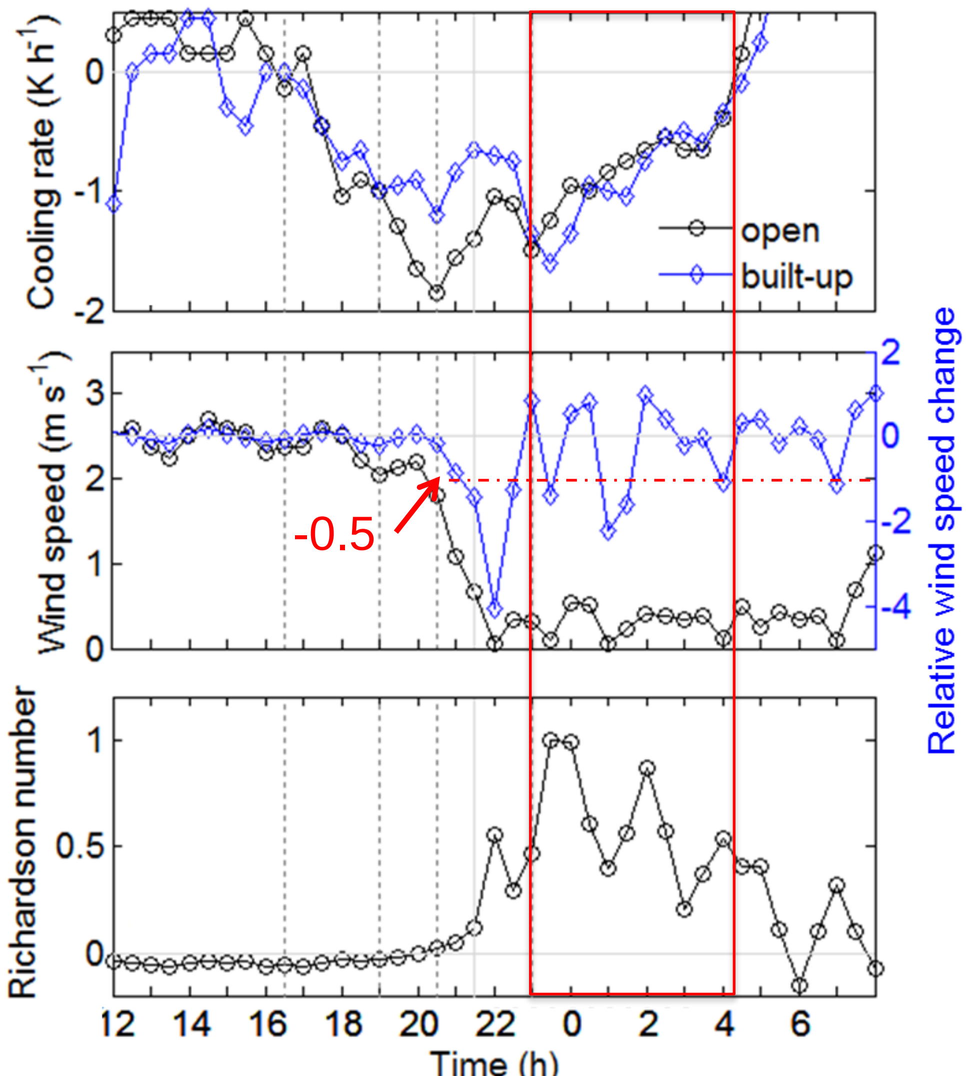

Phase 1 starts when relative wind speed change drops below -0.2.

Most intensive cooling occurs when the atmosphere turns from unstable to stable.

Phase 2 starts about 1 hour after relative wind speed change drops below -0.5.