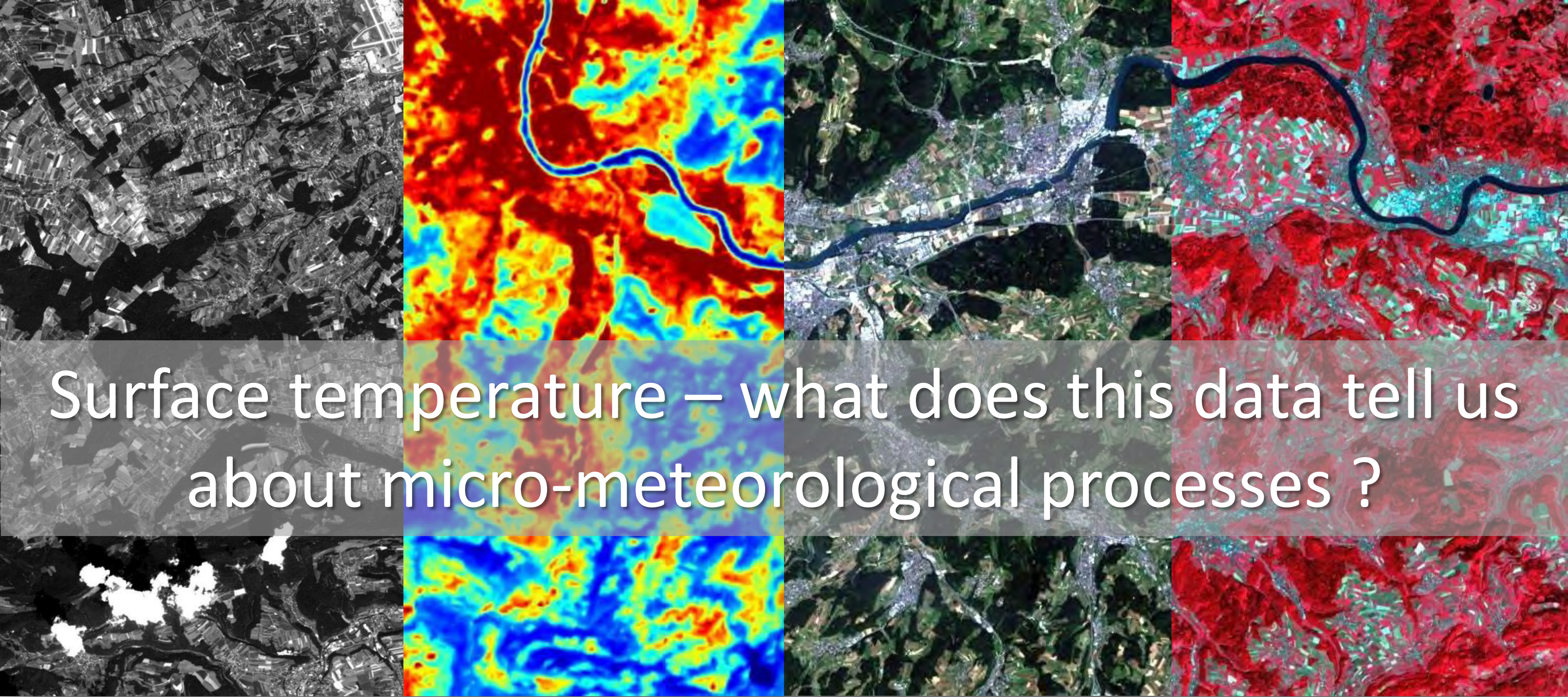


Surface temperature – what does this data tell us about micro-meteorological processes ?

Prof. Dr. Eberhard Parlow

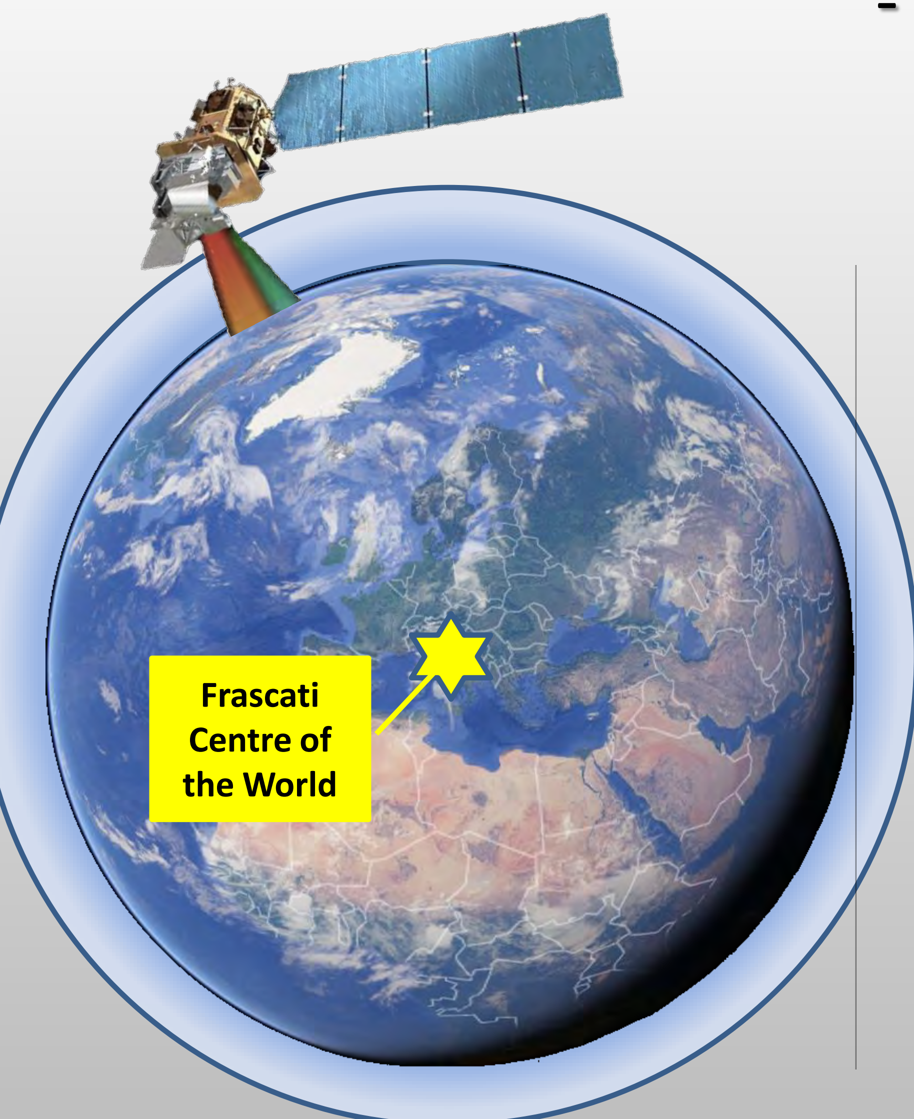
Meteorology, Climatology and Remote Sensing (MCR Lab)

Department of Environmental Sciences

University Basel, Switzerland

eberhard.parlow@unibas.ch - meteo.duw.unibas.ch

What is the satellite measuring in the TIR-bands ?



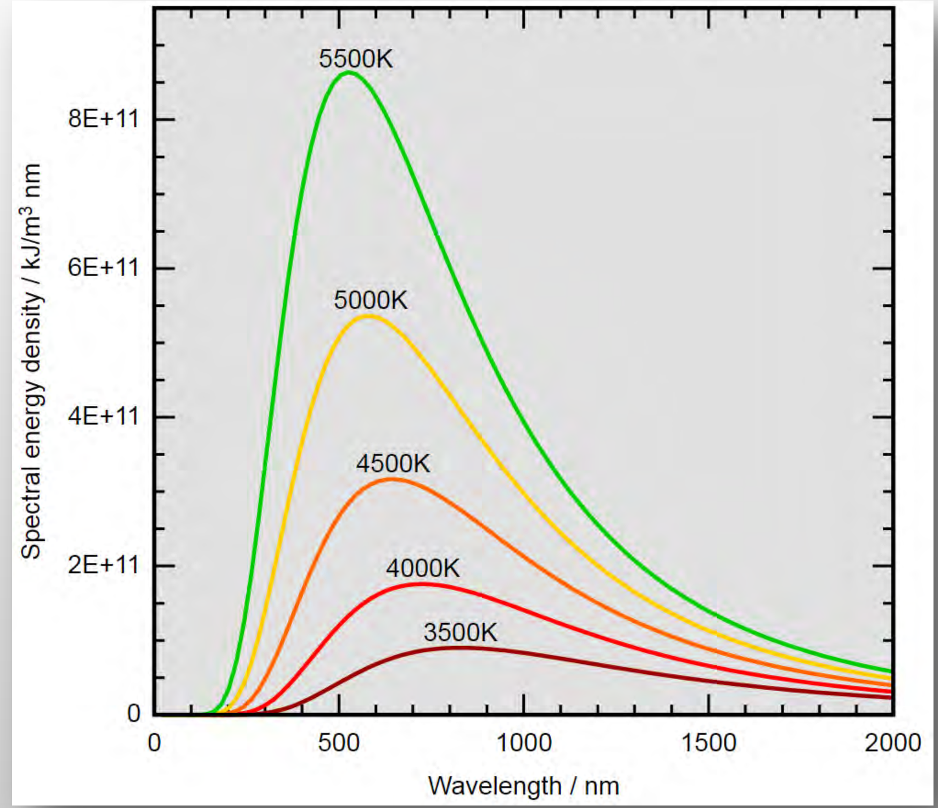
- Longwave terrestrial radiation (> 4 µm) from :
  - Earth surface
  - Atmospheric molecules along path length especially water vapour (H_2O) and ozone (O_3)
  - Aerosols, clouds, dust & haze

  → Atmospheric correction needed to get T_{surf}

Two physical laws are important:

- Wien's displacement law
- Law of Stefan-Boltzmann

Wien's displacement law



$$\lambda T = c = 2897$$

λ : wavelength µm

T : surface temperature K

Describes the shift of the spectrum of black body radiation towards shorter wavelengths as temperature increases.

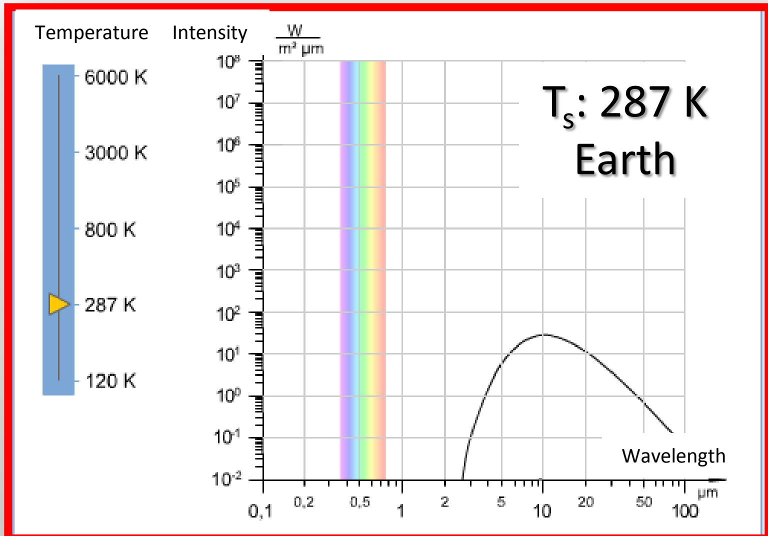
Sun : ≈ 6000 K → λ_{max} ≈ 0.5 µm (visible green)

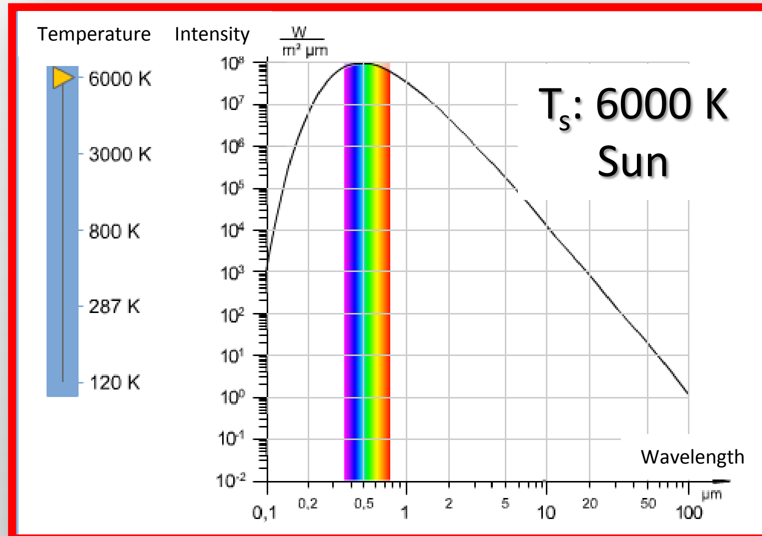
Earth : ≈ 300 K → λ_{max} ≈ 10 µm (thermal infrared)

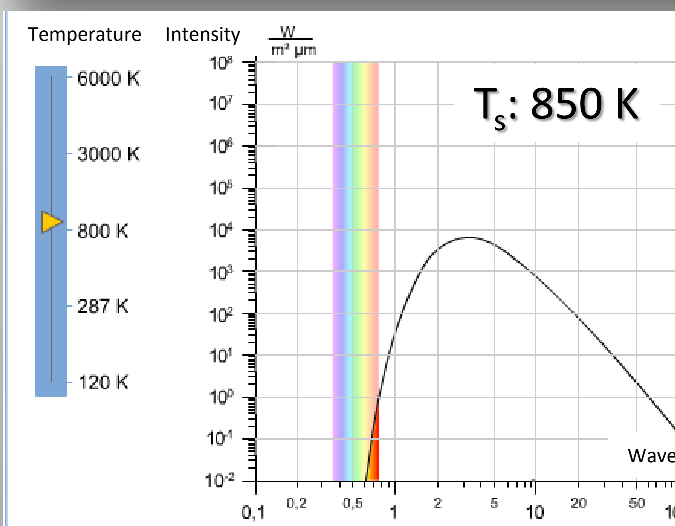
Wilhelm Wien (1864 - 1928) - 1911 Nobel laureate in Physics

Wien’s displacement law

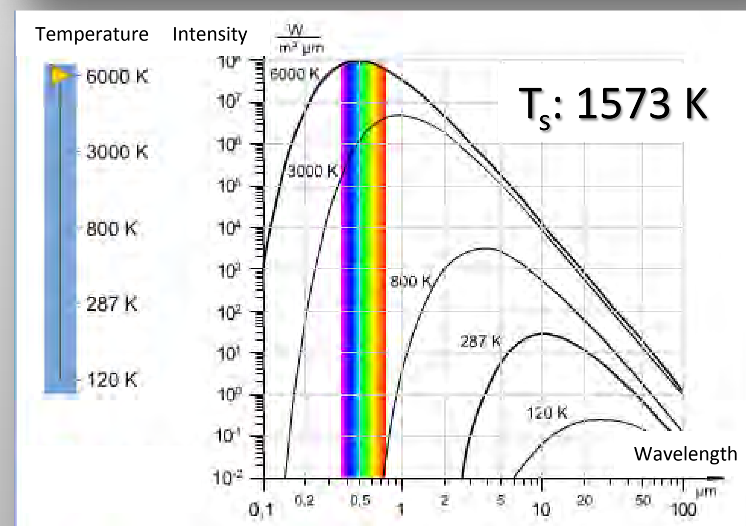
Black body radiation as a function of wavelength for various absolute temperatures.







At 850 K = 577 °C: Iron begins to emit red wavelength (**red heat**). At >1573 K ≈ 1300 °C all visible wave-lengths are emitted (white heat)



Stefan-Boltzmann law

$$Q_l = \sigma \epsilon T^4$$

Q_l : emitted radiation flux density (Wm^{-2} ($Js^{-1}m^{-2}$))

σ : Stefan-Boltzmann constant (5.789 10^{-8} Wm^{-2} K^{-4})

ε : emissivity (black body:1, natural surfaces: 0.9 – 0.98)

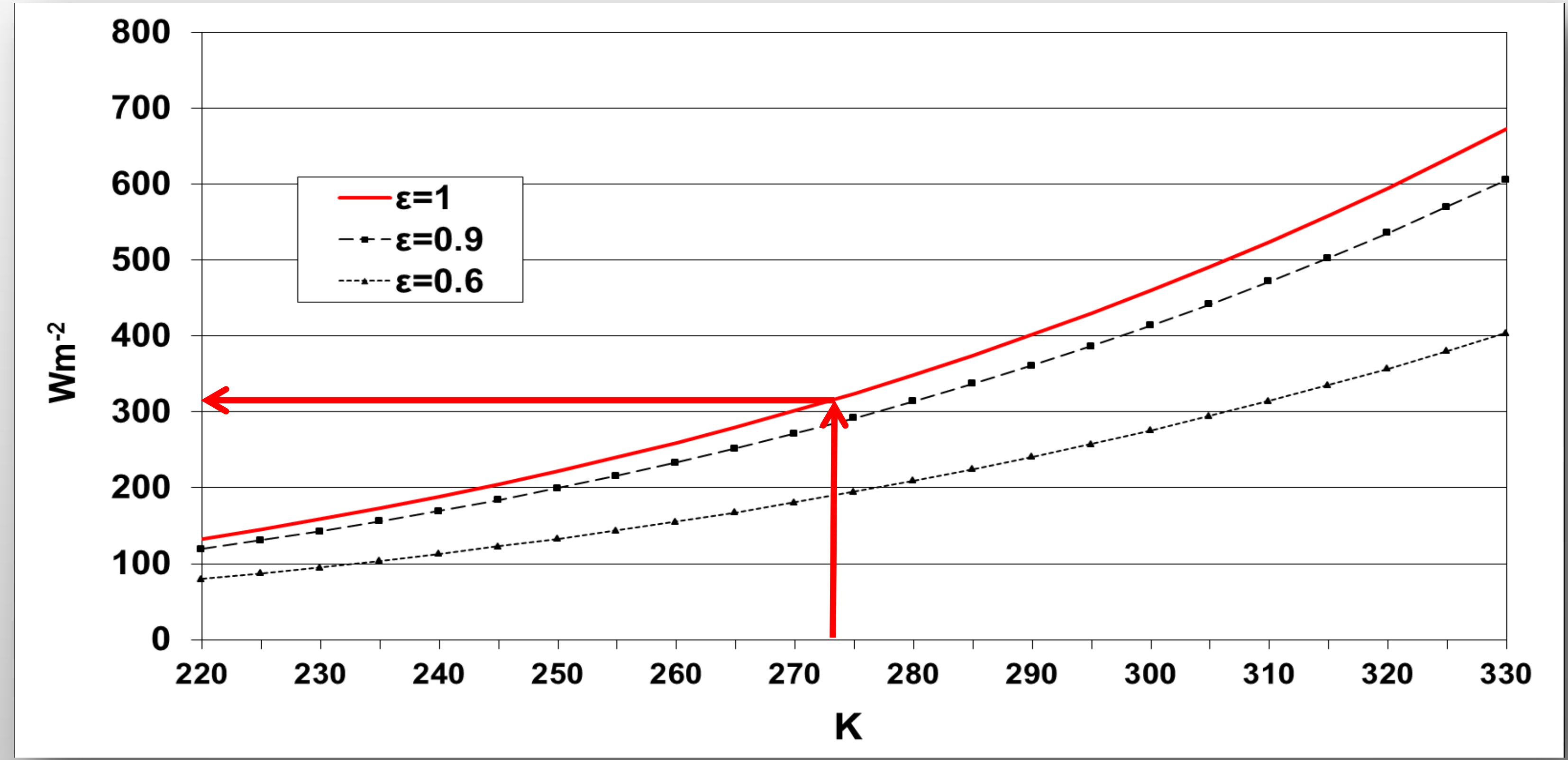
T : surface temperature K

Describes the power radiated from a black body in terms of its temperature. It states that the total energy radiated per unit surface area of a black body across all wavelengths per unit time is directly proportional to the fourth power of the black body's thermodynamic temperature T.

Josef Stefan (1835 - 1893) & Ludwig Boltzmann (1844 – 1906)

Stefan-Boltzmann law

Longwave terrestrial emission as function of temperature



Mnemonic : 273 K = 0 °C : emission is 316 Wm^{-2}

: Δ in 0°C – 15 °C range : 5 Wm^{-2} K^{-1}

: Δ in 15°C – 30 °C range : 6 Wm^{-2} K^{-1}

What is the satellite measuring in the TIR-bands ?

… the satellite measures emitted longwave radiation depending on the surface temperature and according to the Stefan-Boltzmann law !
This emission is a loss of energy for the surface !!

Two technical terms – but they make a difference !

- Surface temperature : the longwave emission of the surface, calibrated and converted to absolute temperatures (K) including surface emissivity correction !
- Brightness temperature : the longwave emission of the surface calibrated and converted to absolute temperatures (K) without emissivity correction ($\varepsilon = 1$, assuming a black body radiator) !

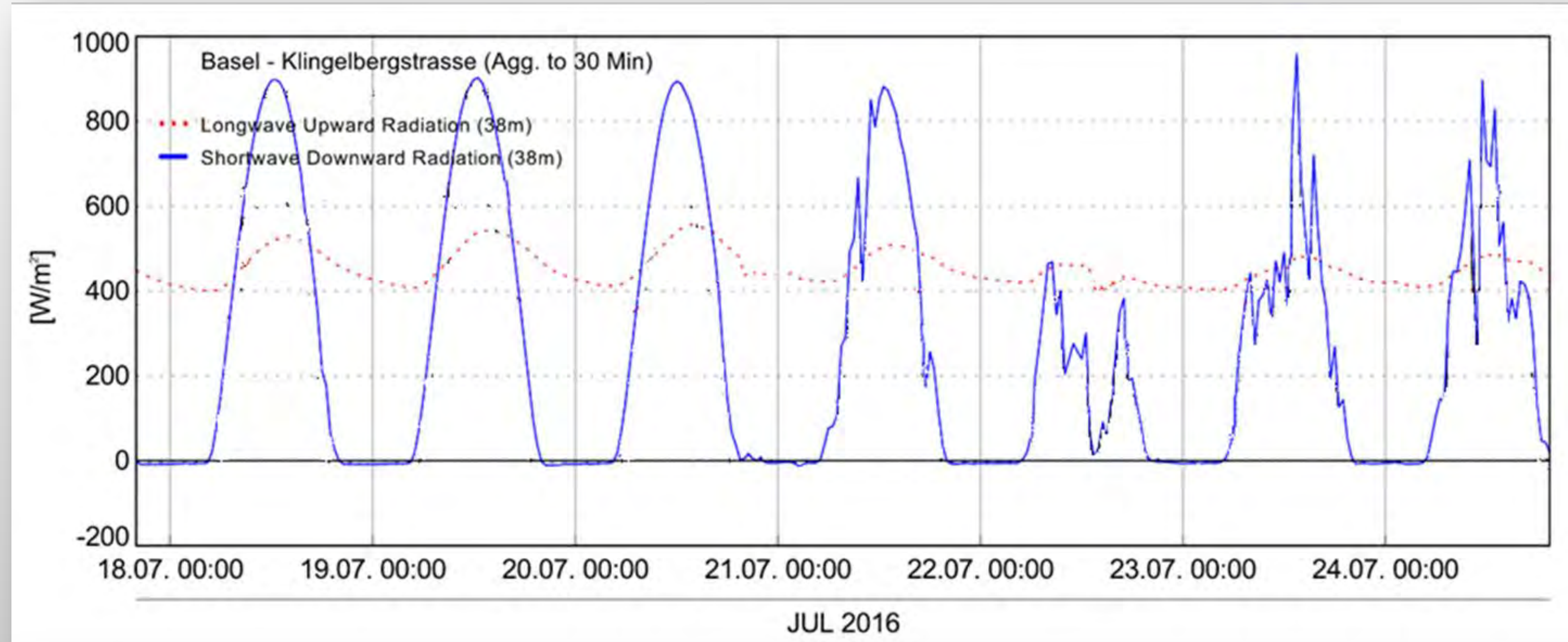
What controls the surface longwave emission?

or – the surface temperature ?

- Solar radiation flux density (W m^{-2})
- Topography (altitude, slope & aspect (m, °, °)
- Vegetation & land use (LULC)
- Surface reflectance (albedo) (%, W m^{-2})
- Air temperature (°C)
- Evapotranspiration rate (W m^{-2})
- Heat conductivity (W K^{-1} m^{-1})
- Heat capacity (J kg^{-1} K^{-1})
- Soil moisture especially top soil moisture (%)
- 3D-structure of surface
- Cloud coverage and cloud temperature (%, °C)
- Wind velocity (m s^{-1})
- .....

What controls the surface longwave emission?

Solar radiation flux density (W m^{-2})

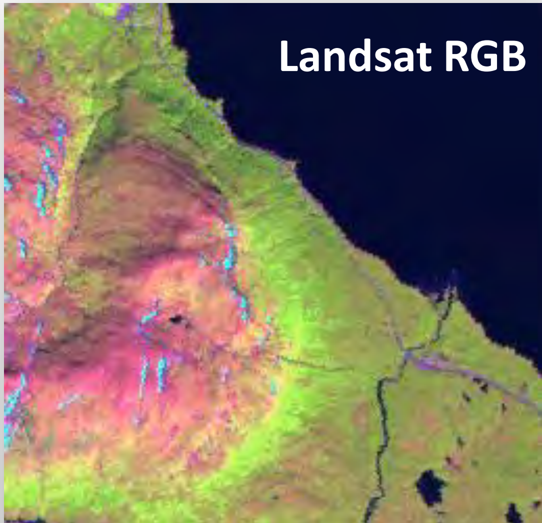


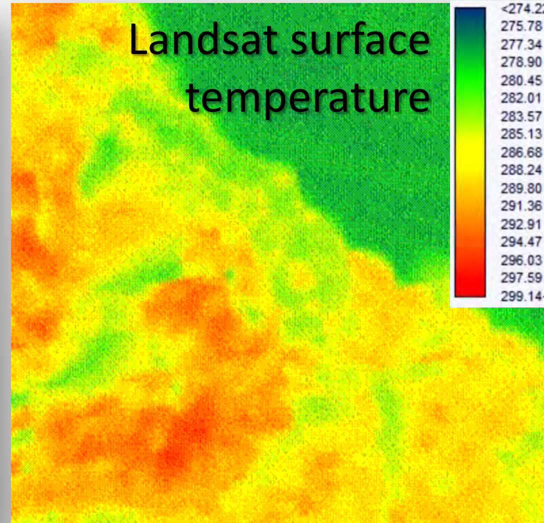
Longwave emission vs solar radiation flux density:

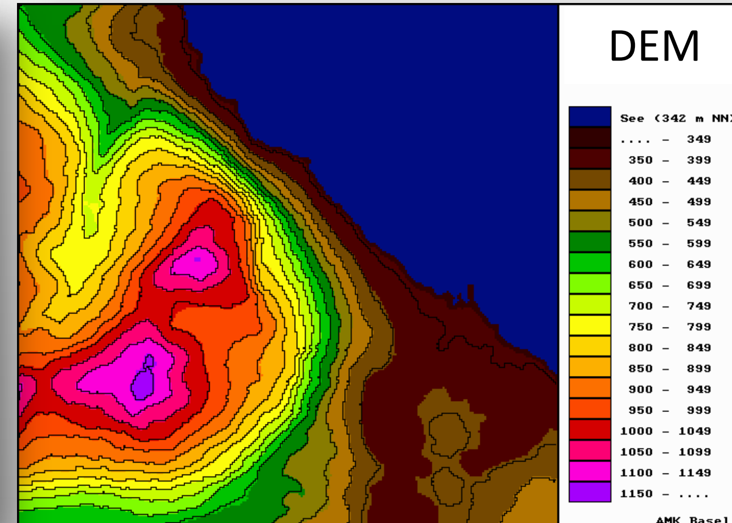
- Smaller amplitude, - Phase shifted due to transport of turbulent sensible heat flux, all day long existing

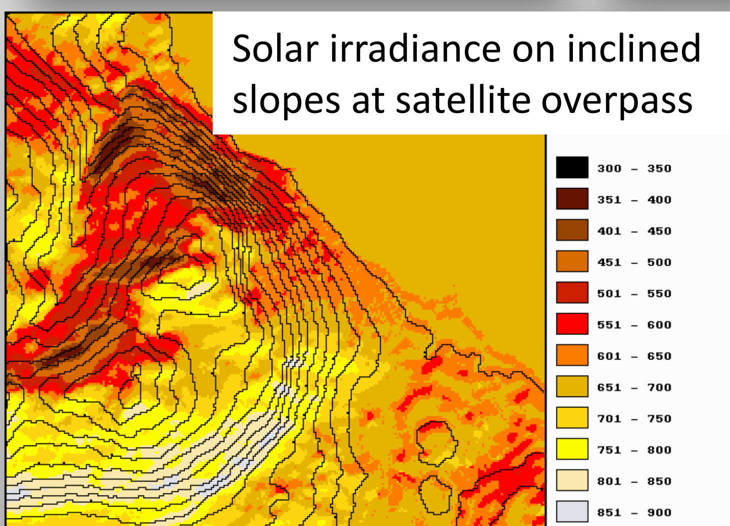
What controls the surface longwave emission?

Topography (altitude, slope & aspect (m, °, °)



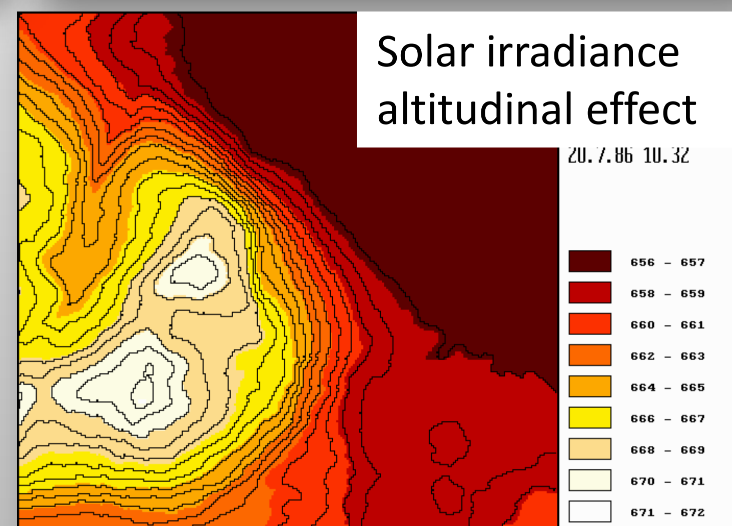






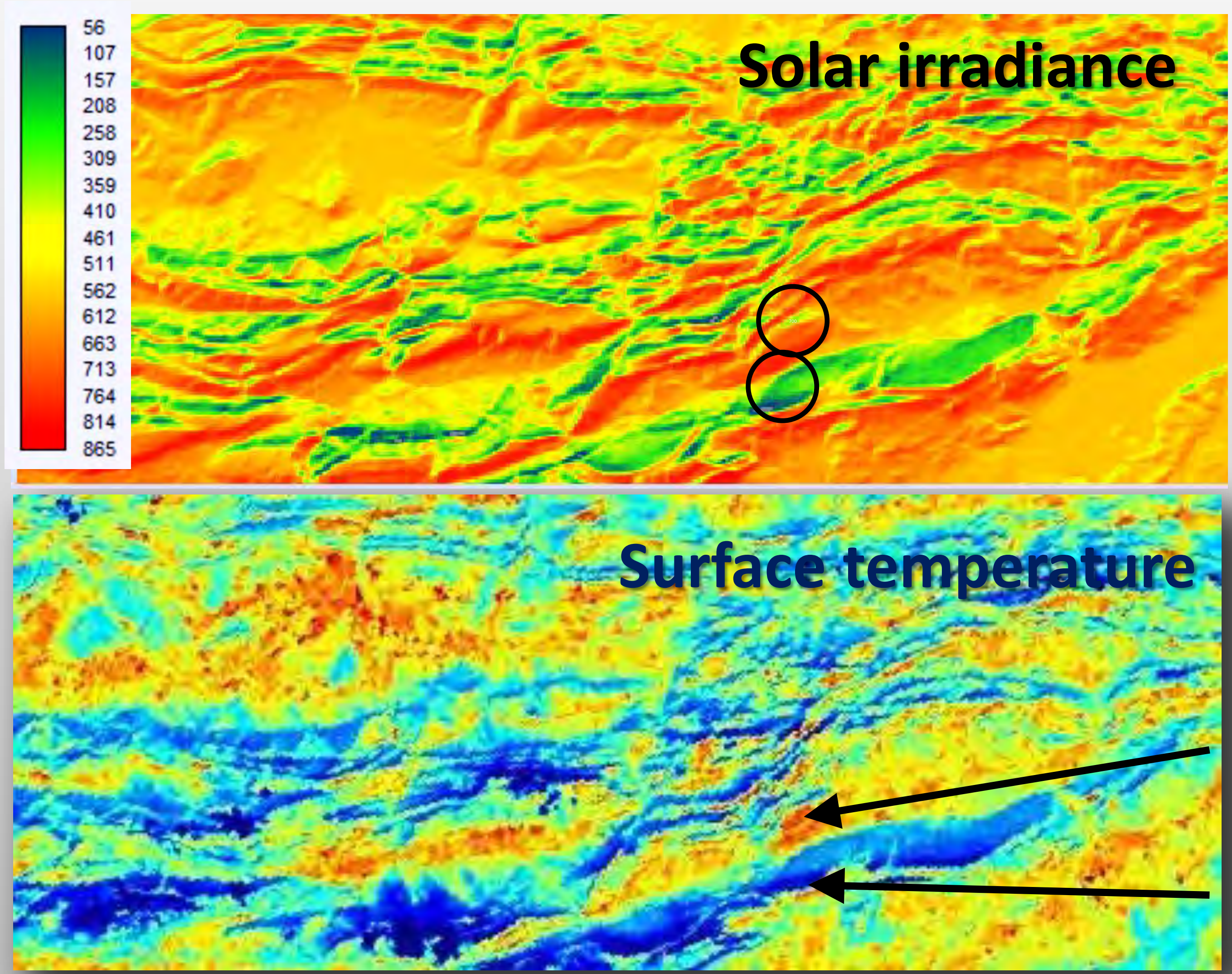
A test site in N-Sweden (Abisko)

Parlow 1988



What controls the surface longwave emission?

Topography (altitude, slope & aspect), solar irradiance



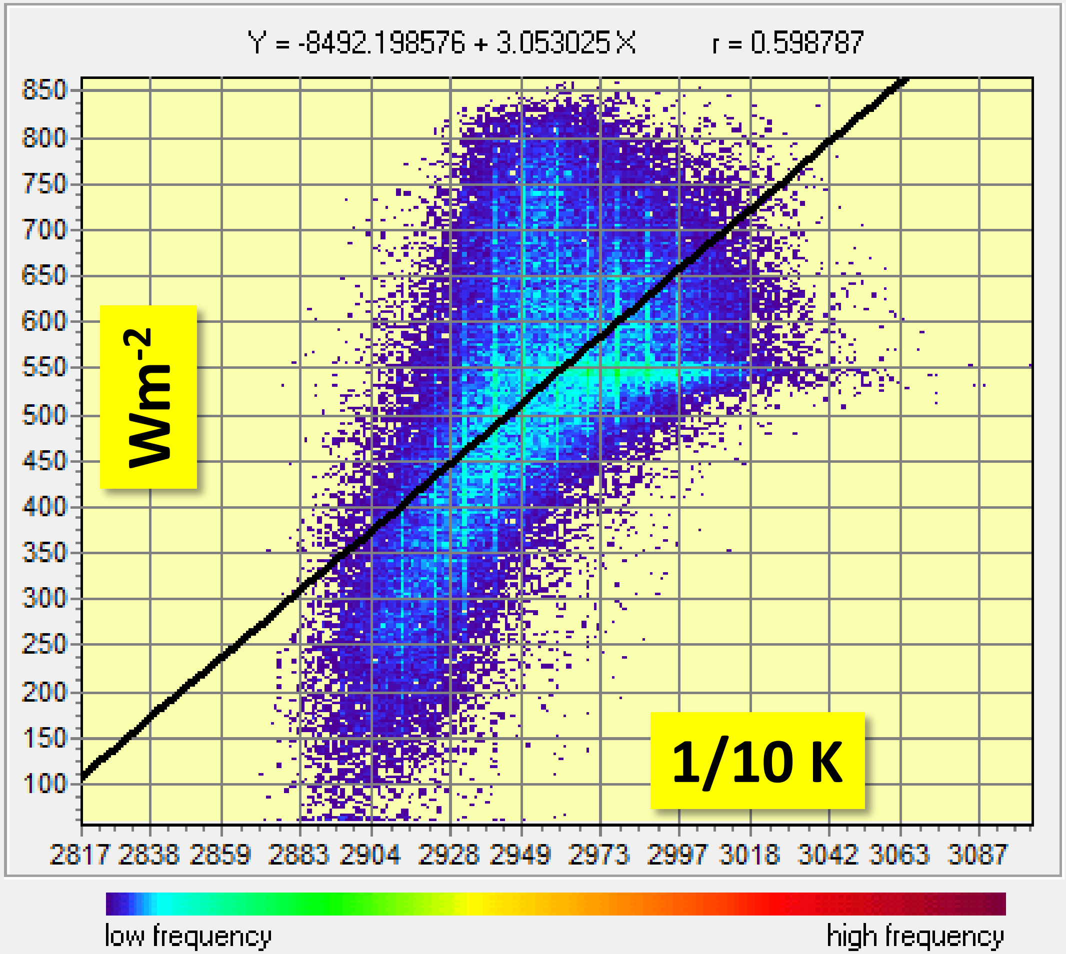
Aspect depending surface temperature in the Swiss Jura Mountains

≈ 298 K = 25 °C

≈ 278 K = 5 °C

What controls the surface longwave emission?

Topography (altitude, slope & aspect), <u>solar irradiance</u>




```
Regression Parameters:

X axis: REGER_TEILRAUM_ALLES-KORRIGIER
Y axis: REGOL_SUEDOBRR_DOY271_INT

Coeff. of Det.          =      35.85 %
Std. Dev. of X          =    29.136207
Std. Dev. of Y          =   148.556241
S.E. of Estimate        =   118.979920
Std. Error of Beta      =     0.012983
t Stat for r or Beta    =   235.158261
t Stat for Beta <> 1    =   158.133575
Sample Size (n)         =        98935
Apparent df             =        98933
```

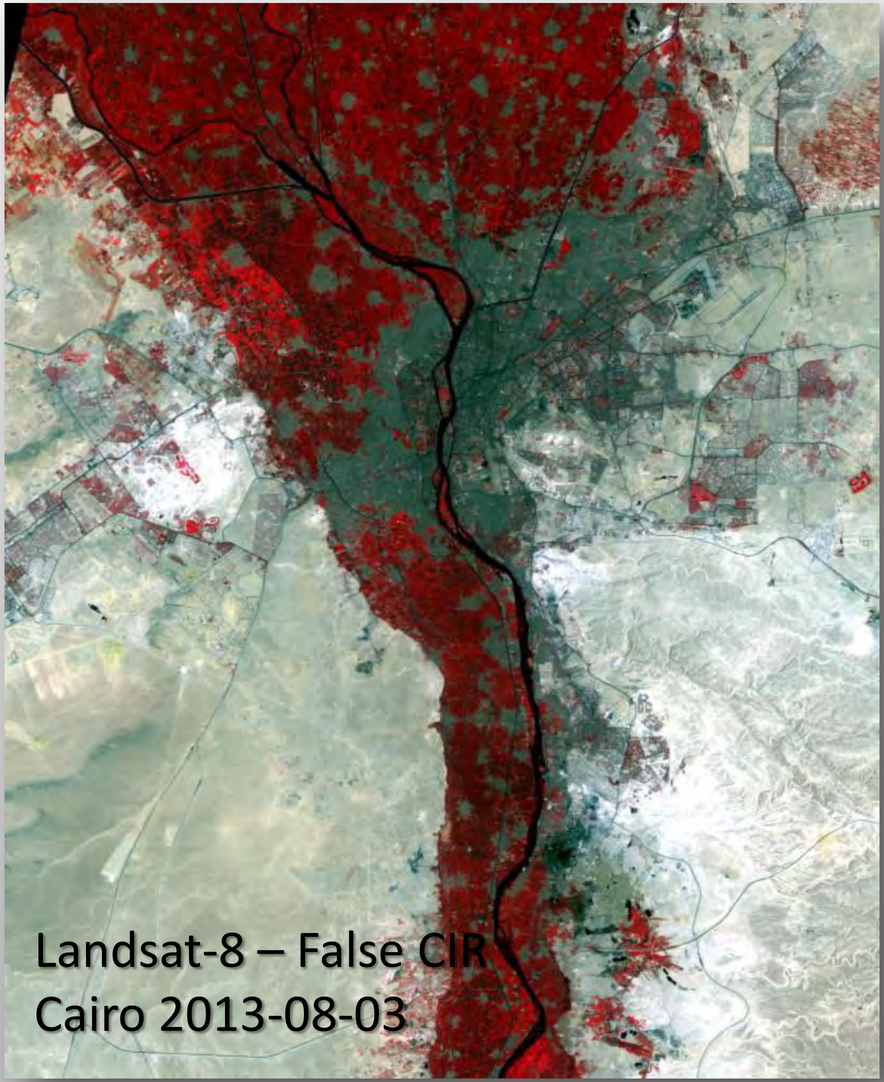
$R^2 = 0.36$

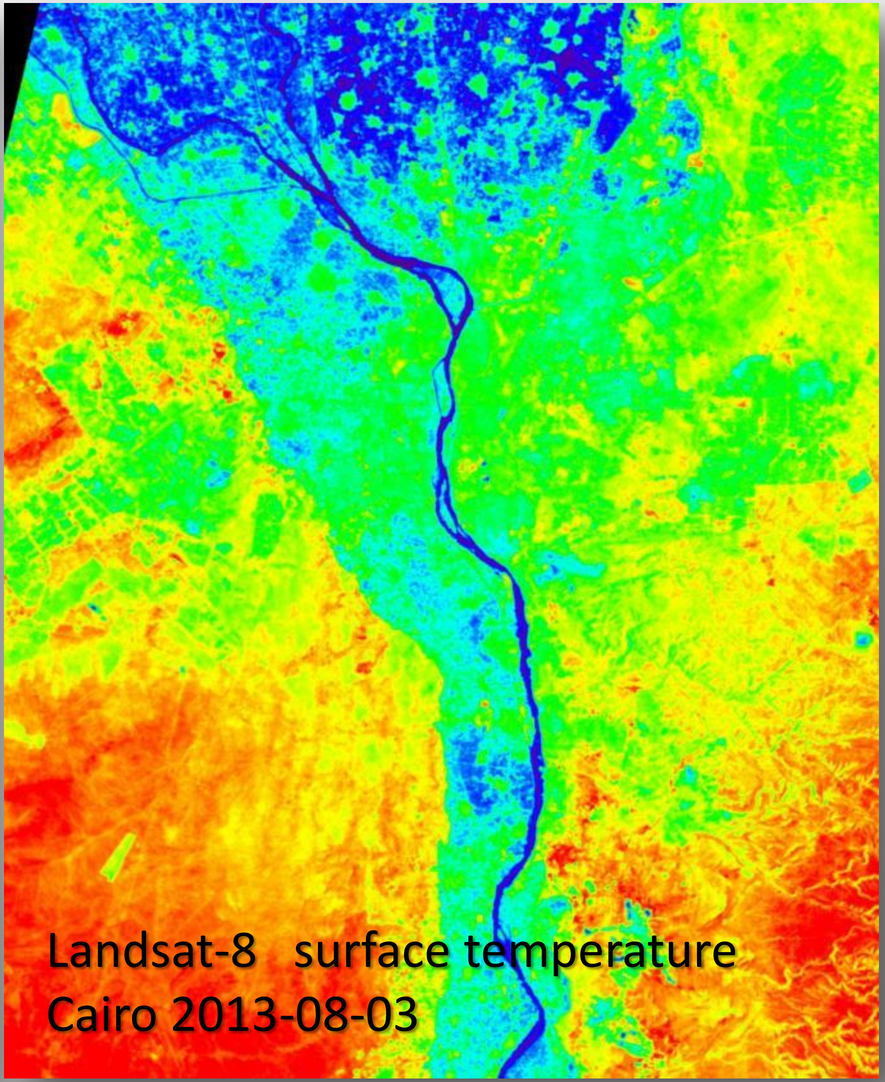
Is not really bad

but it's not enough

What controls the surface longwave emission?

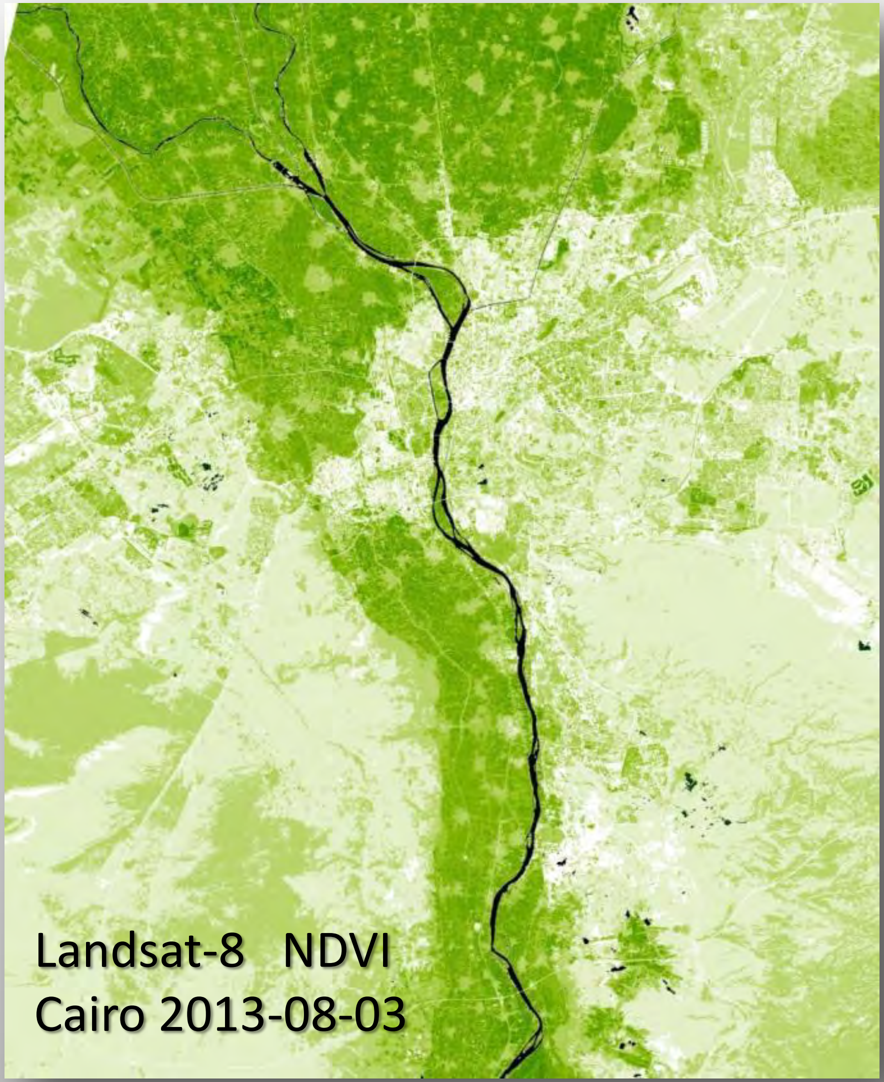
Vegetation and surface reflectance (albedo) (%, W m^{-2})

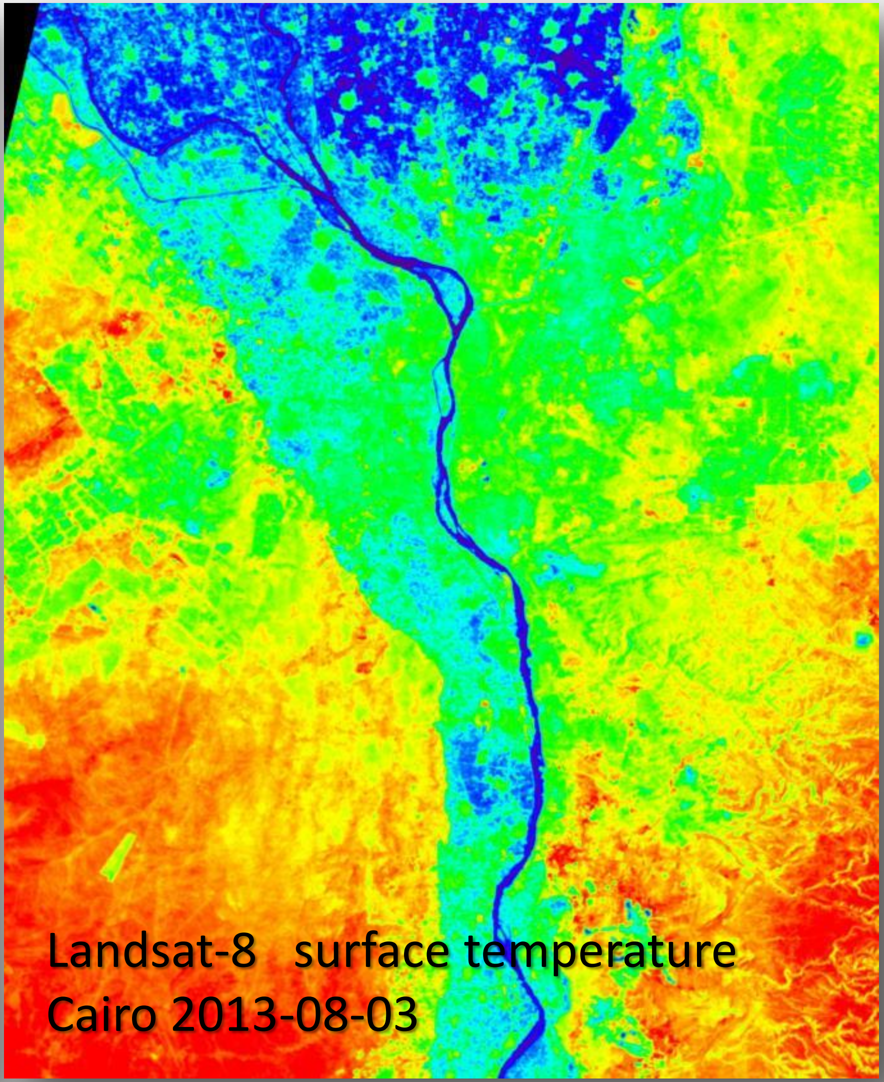




What controls the surface longwave emission?

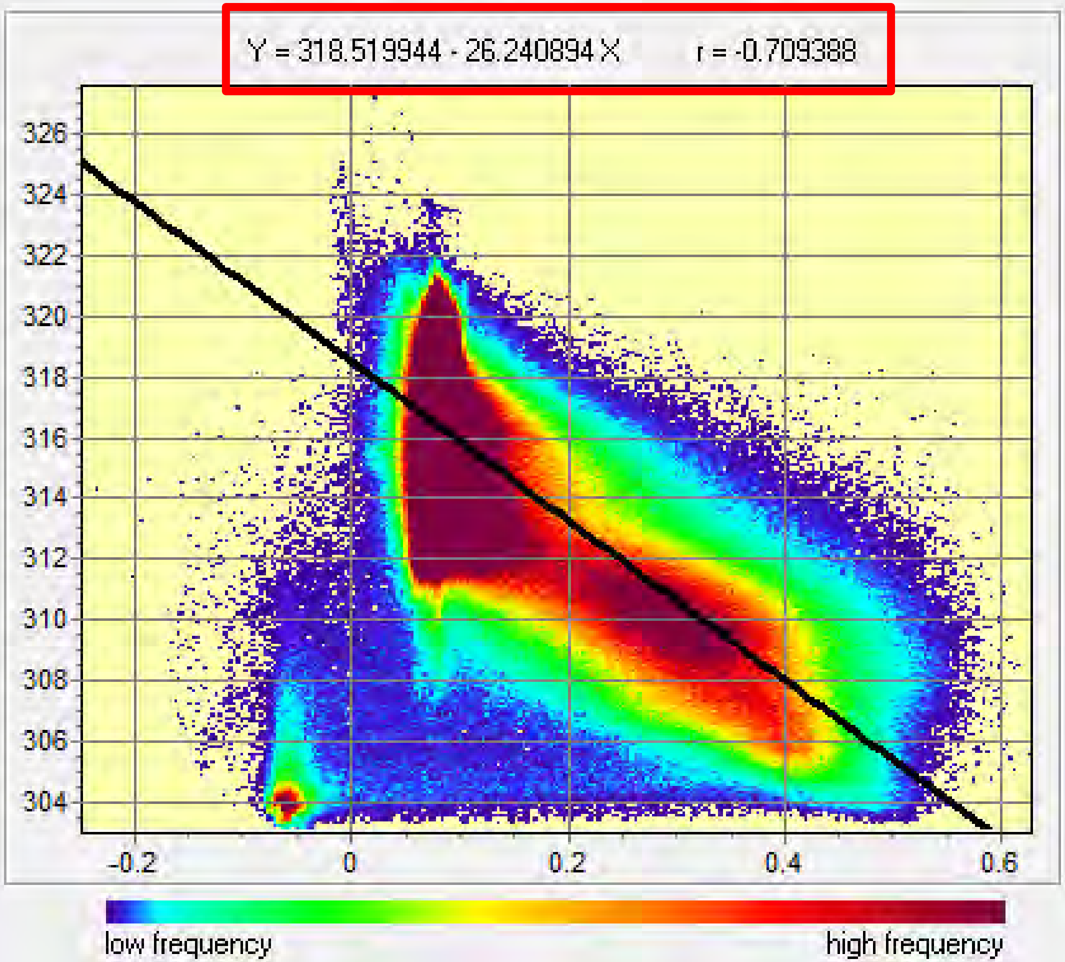
Vegetation and surface reflectance (albedo) (%, W m^{-2})





What controls the surface longwave emission?

Vegetation (NDVI) and surface reflectance



Regression Parameters:

X axis: NDVI_sub
Y axis: Brightness temp_sub

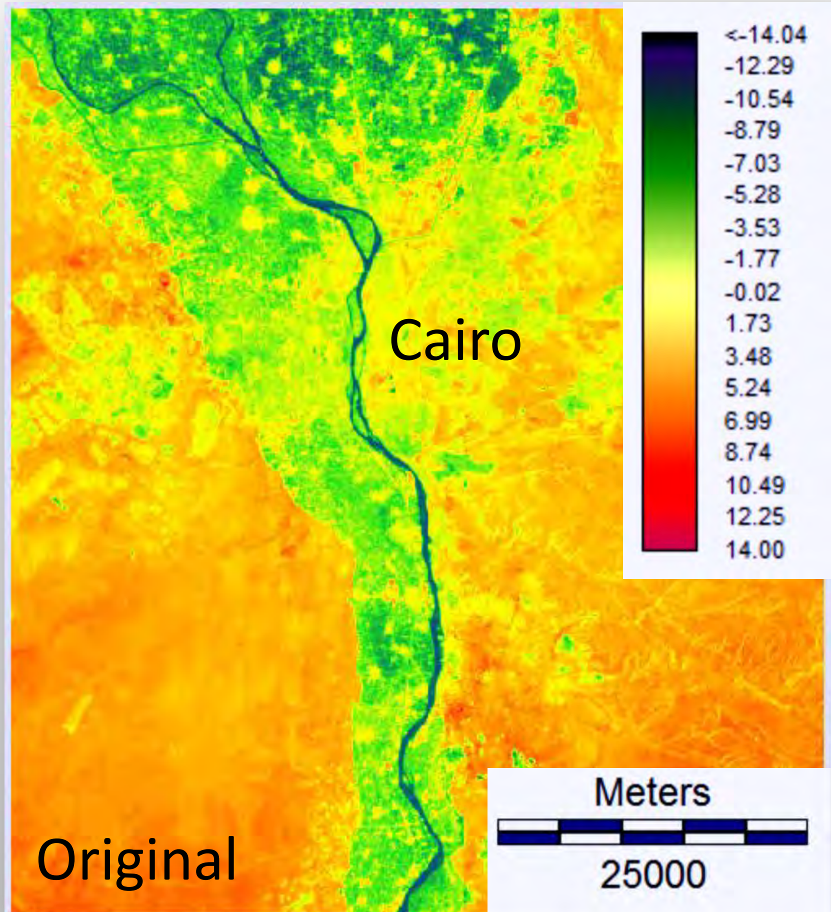
Coeff. of Det.	=	50.32 %
Std. Dev. of X	=	0.098951
Std. Dev. of Y	=	3.660274
S.E. of Estimate	=	2.579827
Std. Error of Beta	=	0.011347
t Stat for r or Beta	=	-2312.499680
t Stat for Beta <> 1	=	-2400.625477
Sample Size (n)	=	5278976
Apparent df	=	5278974

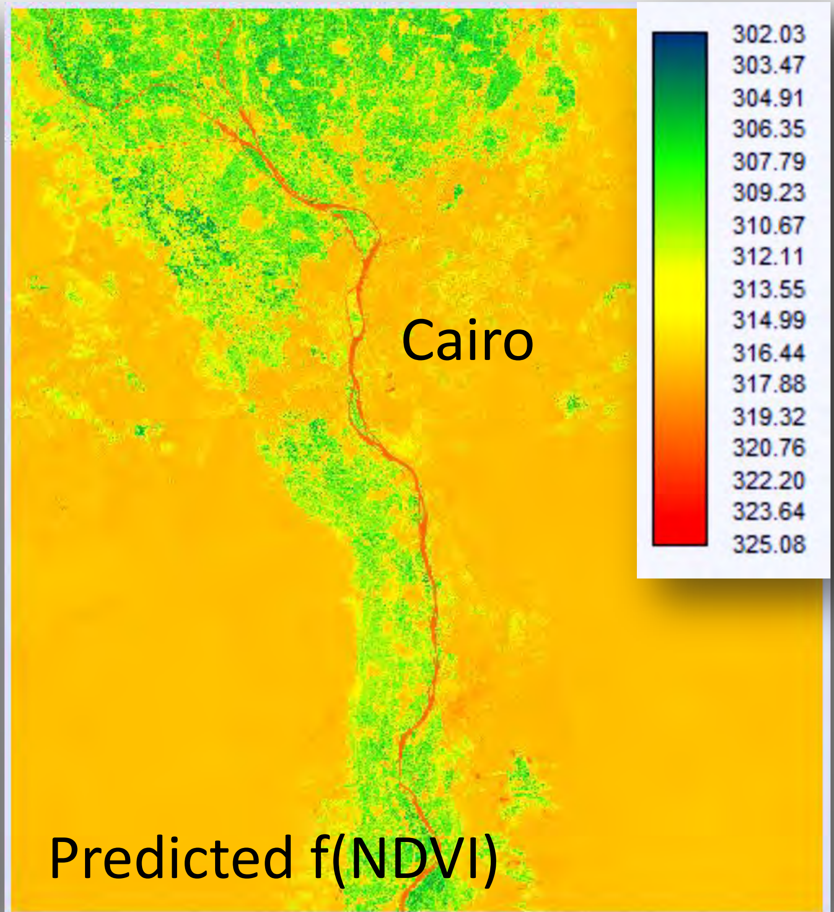
$R^2 = 0.50$

Is not really bad but it's not enough

What controls the surface longwave emission?

Vegetation (NDVI) (T_s = -26.240994 NDVI + 318,519944)

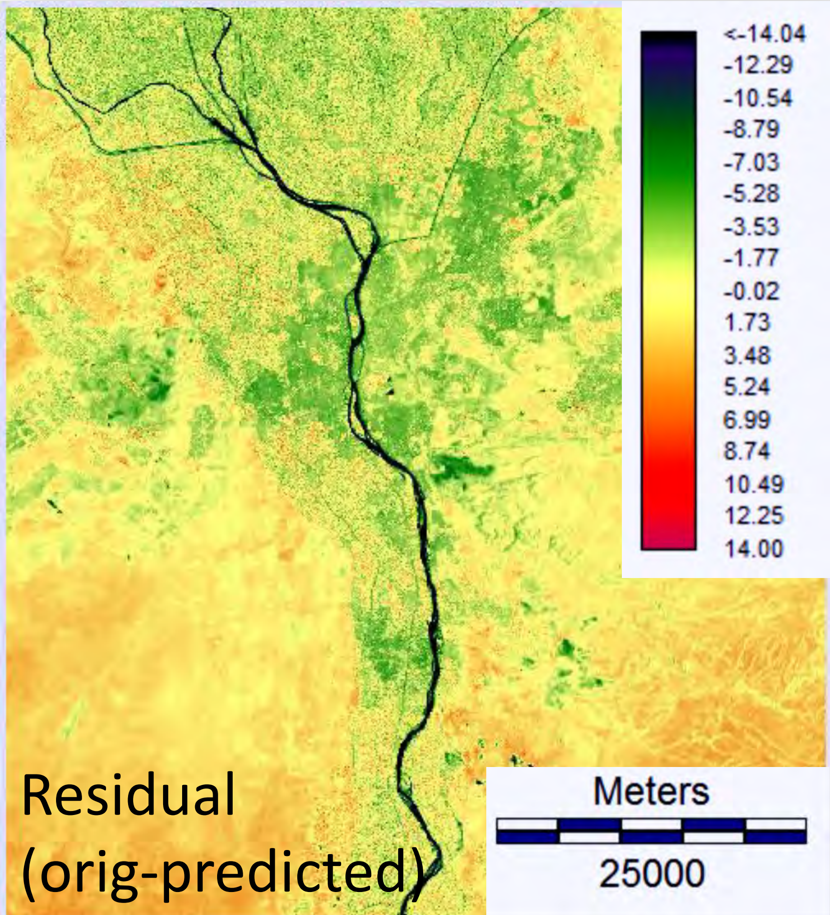


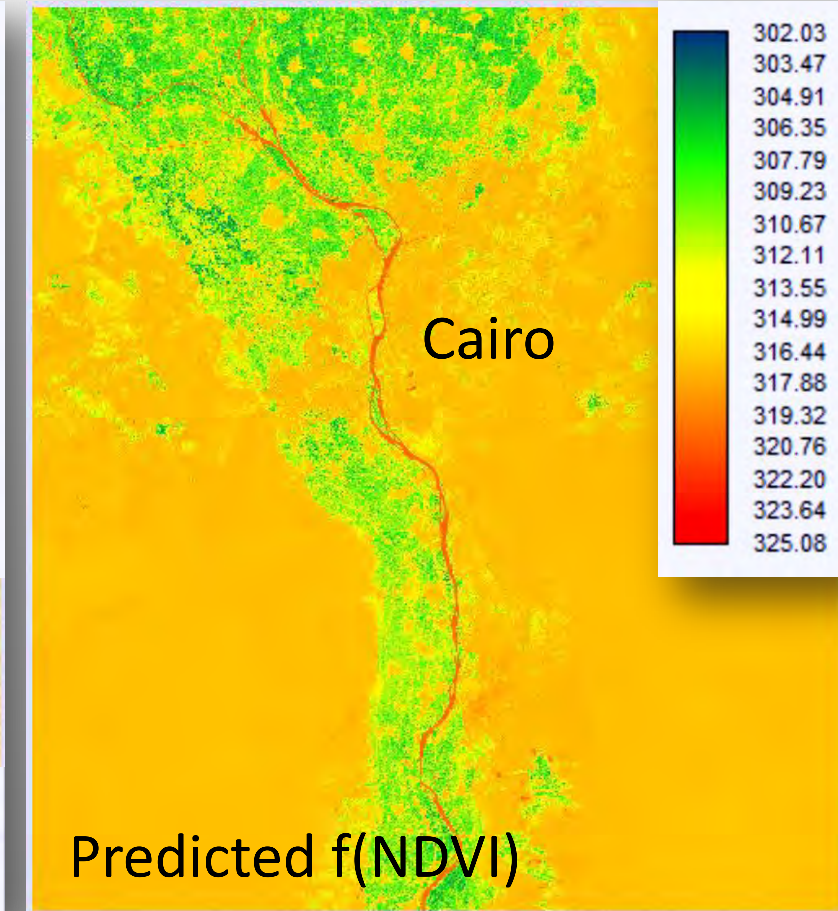


NDVI explains 50 % of surface temperatures, but water is completely wrong (River Nile) and urban areas are also overestimated

What controls the surface longwave emission?

Vegetation (NDVI) (T_s = -26.240994 NDVI + 318,519944)





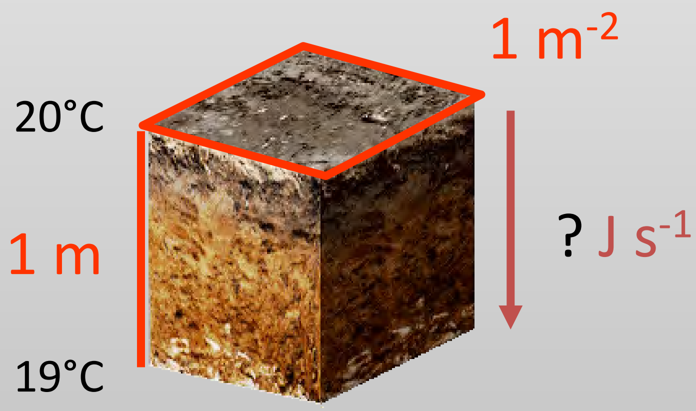
NDVI explains 50 % of surface temperatures, but water is completely wrong (River Nile) and urban areas are also overestimated

What controls the surface longwave emission?

Heat conductivity ($W\ K^{-1}\ m^{-1}$) & heat capacity ($J\ kg^{-1}\ K^{-1}$)

Describes the property of a material to conduct heat.

Energy (J) conducted in the soil per m^2 unit surface and second if temperature gradient is 1 $K\ m^{-1}$.



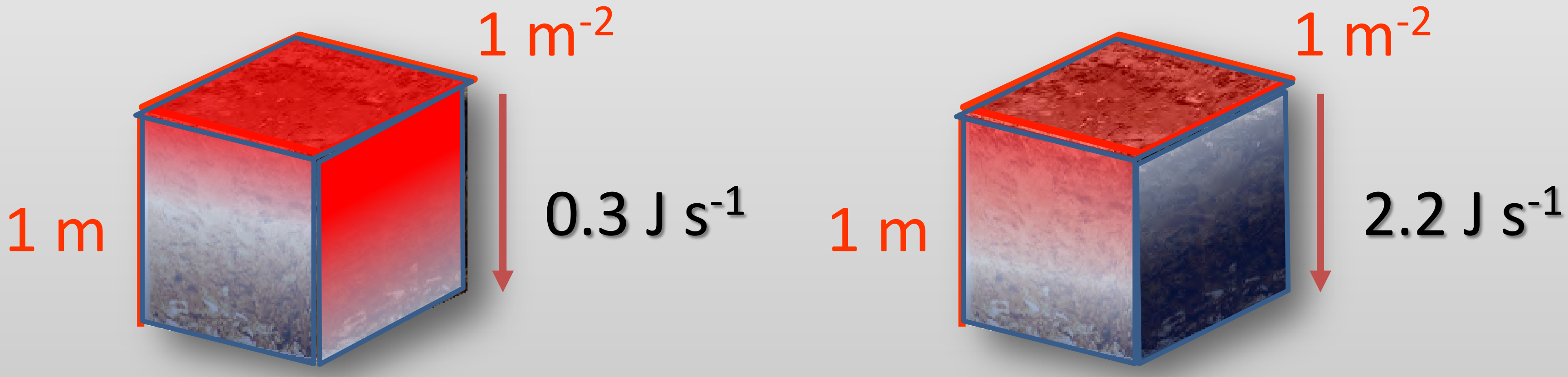
$$J\ s^{-1}\ m^{-2}\ m\ K^{-1} \rightarrow W\ m^{-1}\ K^{-1}$$

Material	Status	Heat conductivity λ ($W\ m^{-1}\ K^{-1}$)
Sandy soil	dry	**0.30**
(40% pore volume)	saturated	**2.20**
Clay	Dry	**0.25**
(40% pore volume)	saturated	**1.58**
Bog soil	dry	**0.06**
(80% pore volume)	saturated	**0.50**
Snow	old	**0.08**
	new	**0.42**
Ice	0 °C, pure	**2.24**
Water	4 °C	**0.57**
Concrete	dense	**1.51**

What controls the surface longwave emission?

Heat conductivity (W K^{-1} m^{-1}) & heat capacity (J m^{-3} K^{-1})

Assuming two cases with equal energy uptake at the surface
e.g. sandy soil dry (left, 0.3 W K^{-1} m^{-1}) and
40 % water saturated (right, 2.2 W K^{-1} m^{-1}).



- Bad heat conductivity
- Strong vertical temperature gradient
- Heat stored close under surface
- High surface temperature

- Good heat conductivity
- Medium vertical temperature gradient
- Heat stored over a bigger volume
- Lower surface temperature

What controls the surface longwave emission?

Heat conductivity (W K^{-1} m^{-1}) & spec. heat capacity (J kg^{-1} K^{-1})

Describes the specific heat needed to raise the temperature of 1 kg of mass by 1 K = the volumetric heat capacity C (J m^{-3} K^{-1}) normalized by the density ρ (kg m^{-3})

$$c = C / \rho$$

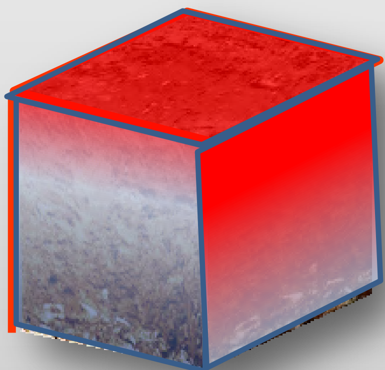
J K^{-1} kg^{-1}

Material	Status	Specific heat capacity *c* (J kg^{-1} K^{-1} x 10^3)
Sandy soil	dry	**800**
(40% pore volume)	saturated	**1480**
Clay	dry	**890**
(40% pore volume)	saturated	**1550**
Bog soil	dry	**1920**
(80% pore volume)	saturated	**3650**
Snow	old	**2090**
	new	**2090**
Ice	0 °C, pure	**2100**
Water	4 °C	**4180**
Concrete	dense	**880**

What controls the surface longwave emission?

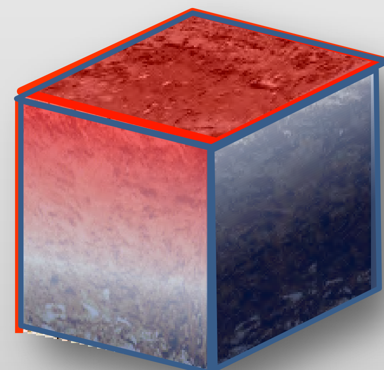
Heat conductivity (W K^{-1} m^{-1}) & heat capacity (J kg^{-1} K^{-1})

Assuming two cases with equal energy uptake at the surface
e.g. sandy soil dry (left, 890×10^3 J K^{-1} kg^{-1}) and
40 % water saturated (right, 1400×10^3 J K^{-1} m^{-1})



890×10^3 J K^{-1} kg^{-1}

- Low heat capacity
- Heat uptake leads to fast tempera-ture increase
- High surface temperature

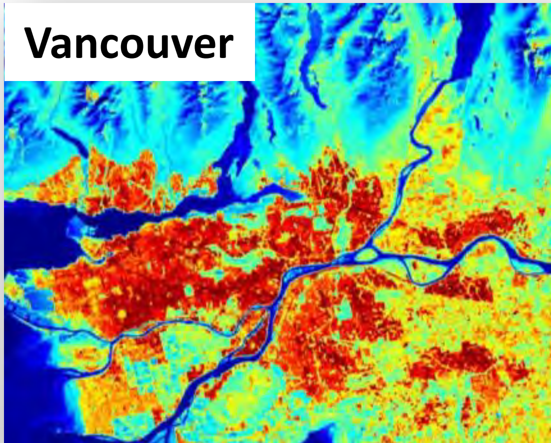


1400×10^3 J K^{-1} kg^{-1}

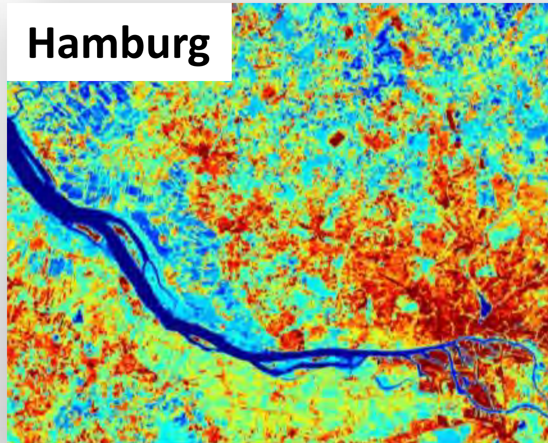
- High heat capacity
- Heat uptake leads to slow temperature increase
- Lower surface temperature

Due to very high heat capacity of water all materials with higher water content heat up or cool down quite slowly !

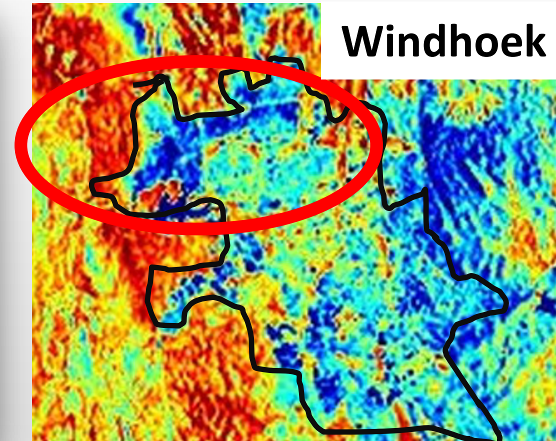
What controls the surface longwave emission?



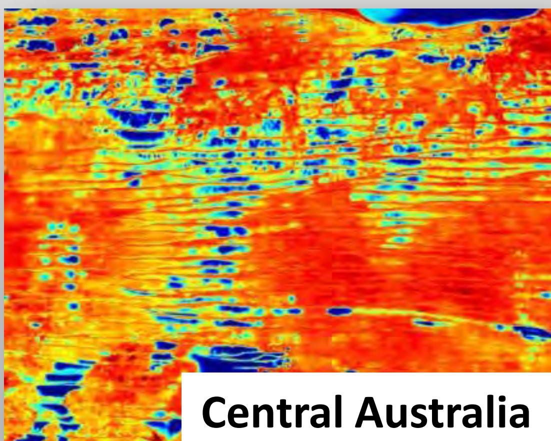
Surface properties/altitude



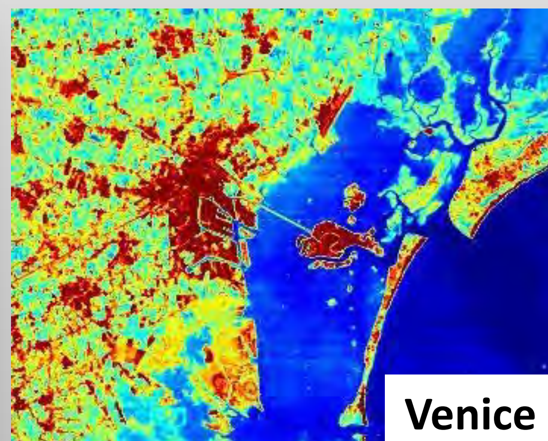
Surf. properties/soil wetness



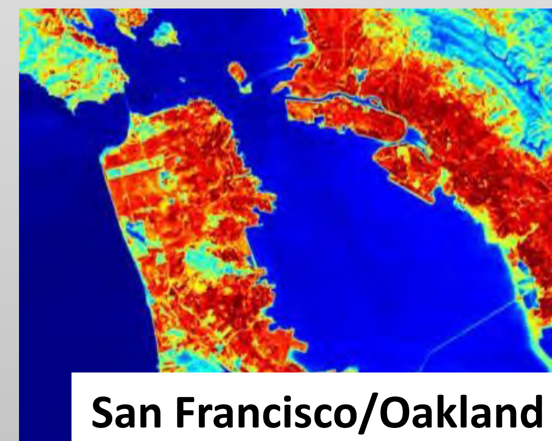
Surf. Properties/emissivity



Soil wetness

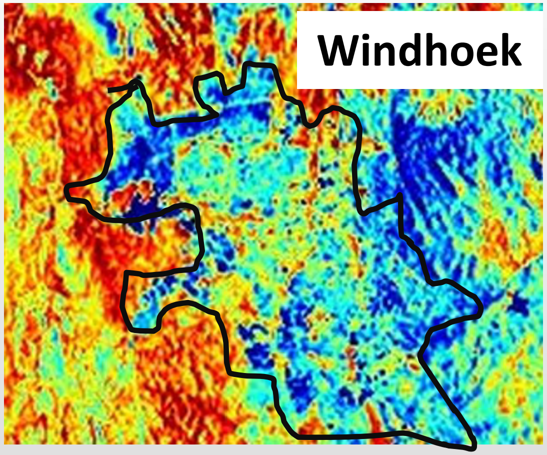


Surf. properties/soil wetness



Surface properties

What controls the surface longwave emission?



Surf. Properties/emissivity

Interactions of radiation and heat fluxes

The radiation budget seen as a "bank account"

Item	Incomes	Expenditures
Salary	5000	
Rent & insurance		1500
Add. income	1000	
Food etc		4000
Sum inc./expend.	6000	5500
Balance	**+ 500**	

$$Q^* = KW\downarrow - KW\uparrow + LW\downarrow - \mathbf{LW\uparrow}$$

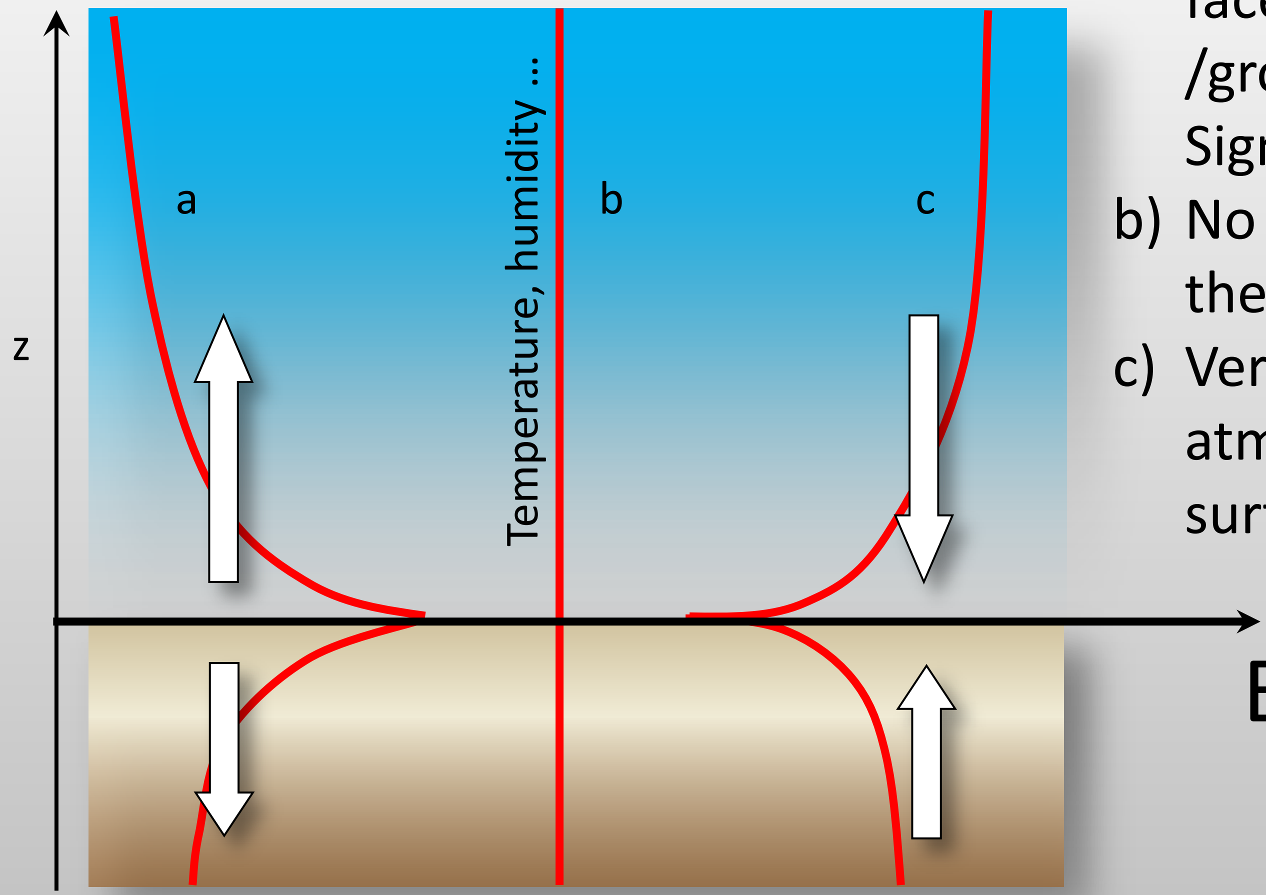
$$Q^* = KW\downarrow (1-\alpha) + LW\downarrow - \boldsymbol{\varepsilon\sigma T_0^4}$$

Q^*: net radiation, KW: solar, LW: terrestrial, ↓ ↑: in/out

α : albedo ; Q^* can be >0, =0, <0 !!

Heat fluxes and gradients

What determines heat fluxes ?



a) Vertical heat flux from surface towards atmosphere /ground
   Sign : –
b) No vertical gradient and therefore no heat flux
c) Vertical heat flux from atmosphere/ground towards surface. Sign : +

Earth surface

Without gradients – no heat fluxes !!!!

Interaction of radiation and heat fluxes

The complete heat budget

$$Q^* + Q_H + Q_E + Q_S + Q_A + Q_P = 0 \quad [\mathrm{W\ m^{-2}}]$$

Q* : net radiation (sum of all short- and longwave radiation fluxes)

Q_H : sensible heat flux density (temperature)

Q_E : latent heat flux density (evapotranspiration)

Q_S : storage heat flux density / ground heat flux density

Q_A : anthropogenic heat flux density (the great unknown)

Q_P : photosynthetic heat flux density (very small)

$Q^* - Q_G$: available energy „for turbulent heat exchange“

The equation is 0 because it refers to a surface which has no mass !!

Radiation and Heat Fluxes at daytime

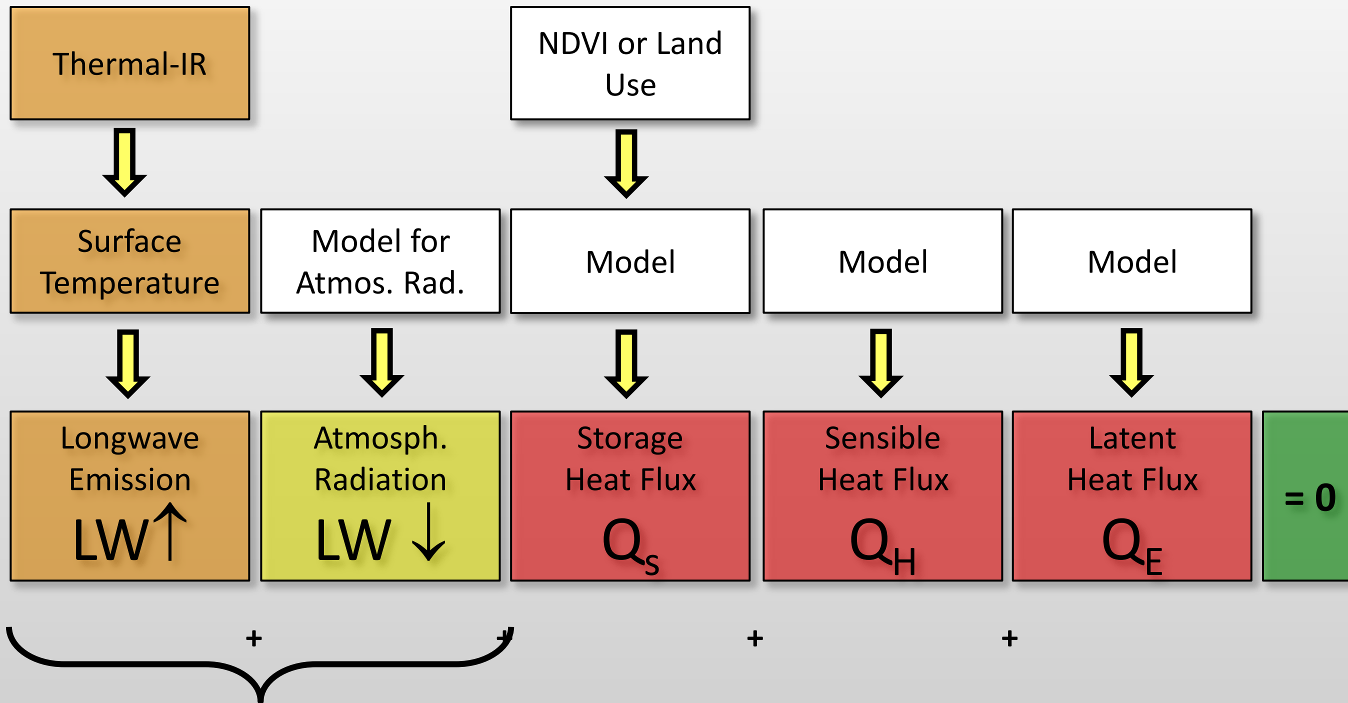
The surface temperature is only a small part of the radiation and complete heat budget

Surface Model	Multispectral Data	Thermal-IR		NDVI or Land Use			
⇓	⇓	⇓		⇓			
Radiation Model	Surface Albedo	Surface Temperature	Model for Atmos. Rad.	Model	Model	Model	
⇓	⇓	⇓	⇓	⇓	⇓	⇓	
Solar Irradiance KW ↓	Shortwave Reflexion KW↑	Longwave Emission LW↑	Atmosph. Radiation LW ↓	Storage Heat Flux Q_S	Sensible Heat Flux Q_H	Latent Heat Flux Q_E	**= 0**
+	+	+	+	+	+		

Net radiation <u>daytime</u>: Q* = KW ↓ - KW↑ + LW ↓ - LW↑

Q* is mostly > 0 and therefore radiative energy is available for the various heat fluxes !

Radiation and Heat Fluxes at night-time



Net radiation <u>night-time</u>: Q* = LW ↓ - LW↑

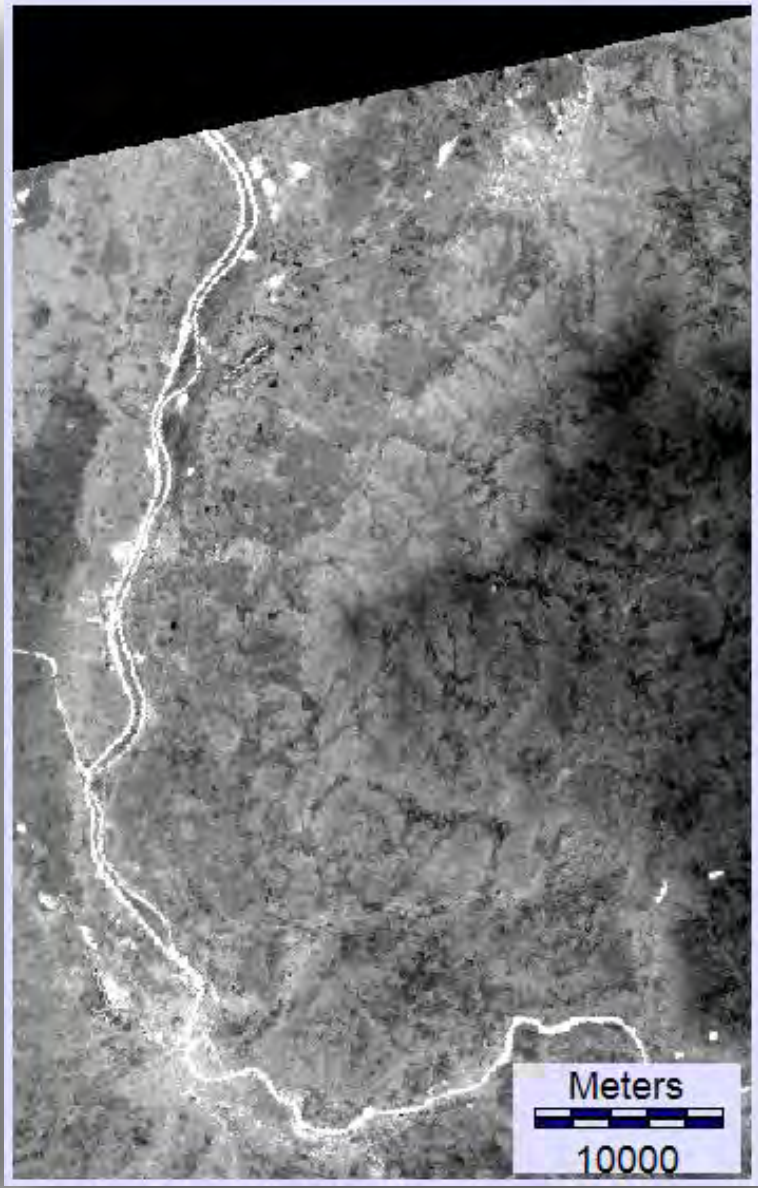
Q* is mostly < 0 and heat fluxes must compensate negative net radiation. This leads to cooling of air and soil or condensation of water vapour.

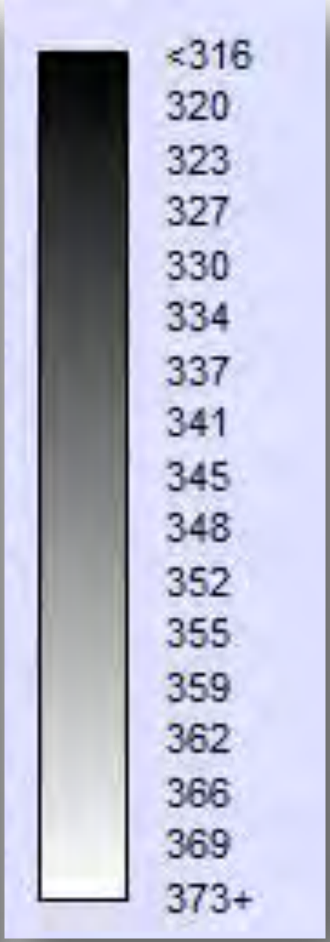
Landsat CIR 4-3-2 image of SW-Black Forest

Forest LULC is left visible.

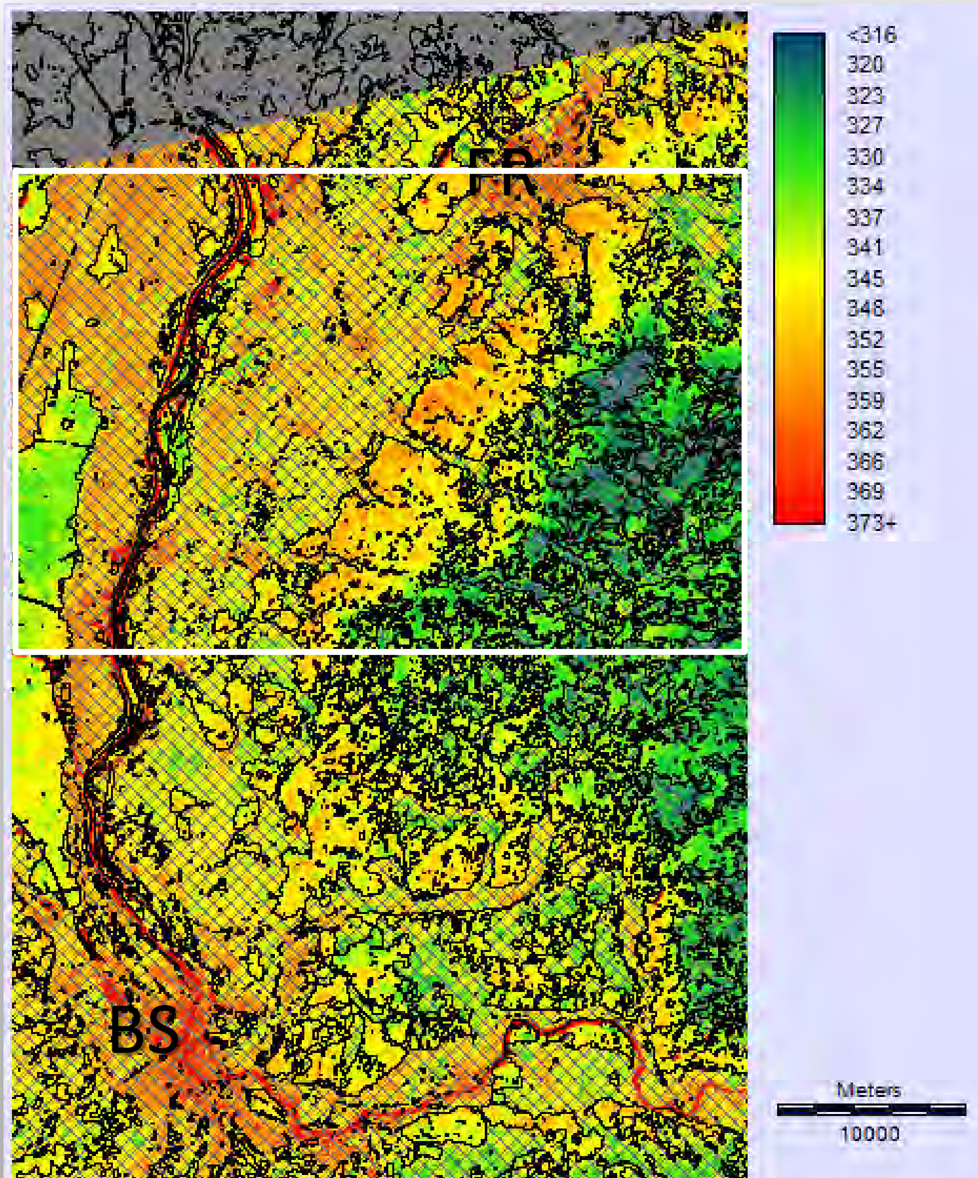
- Some forests at the Upper Rhine Plains.
- Forested areas at western slopes of Black Forest.

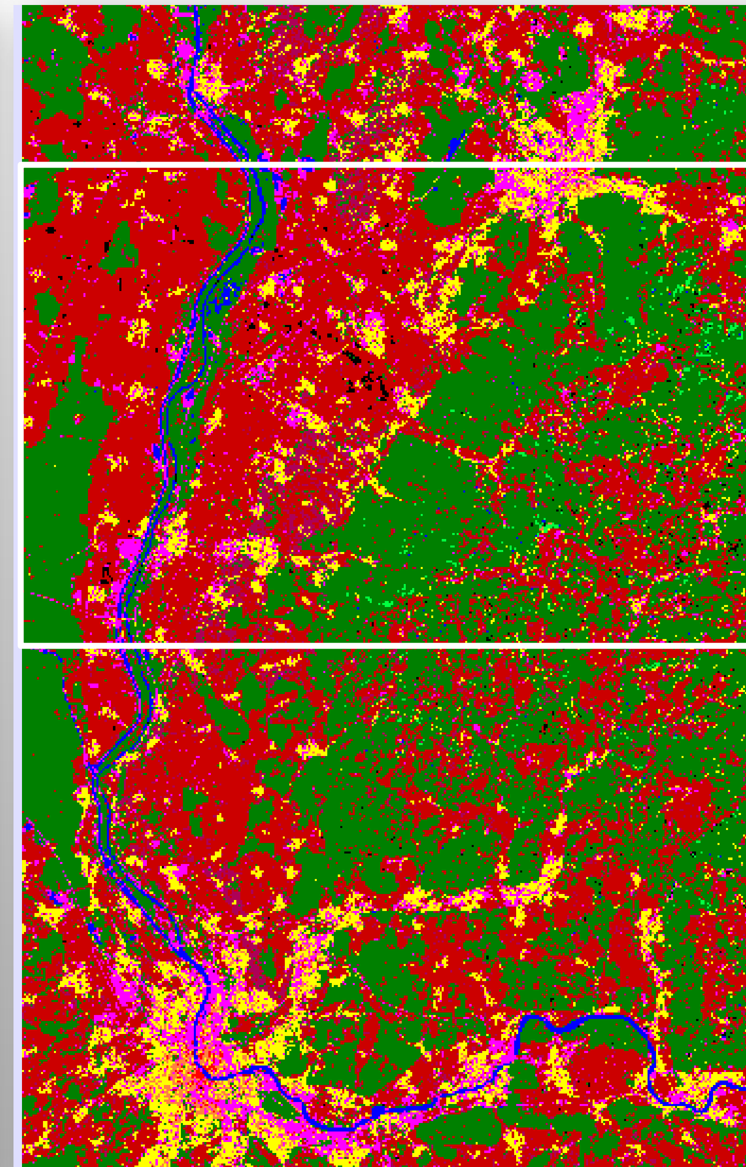
Aster Night LW-emission SW-Black Forest (Wm^{-2})



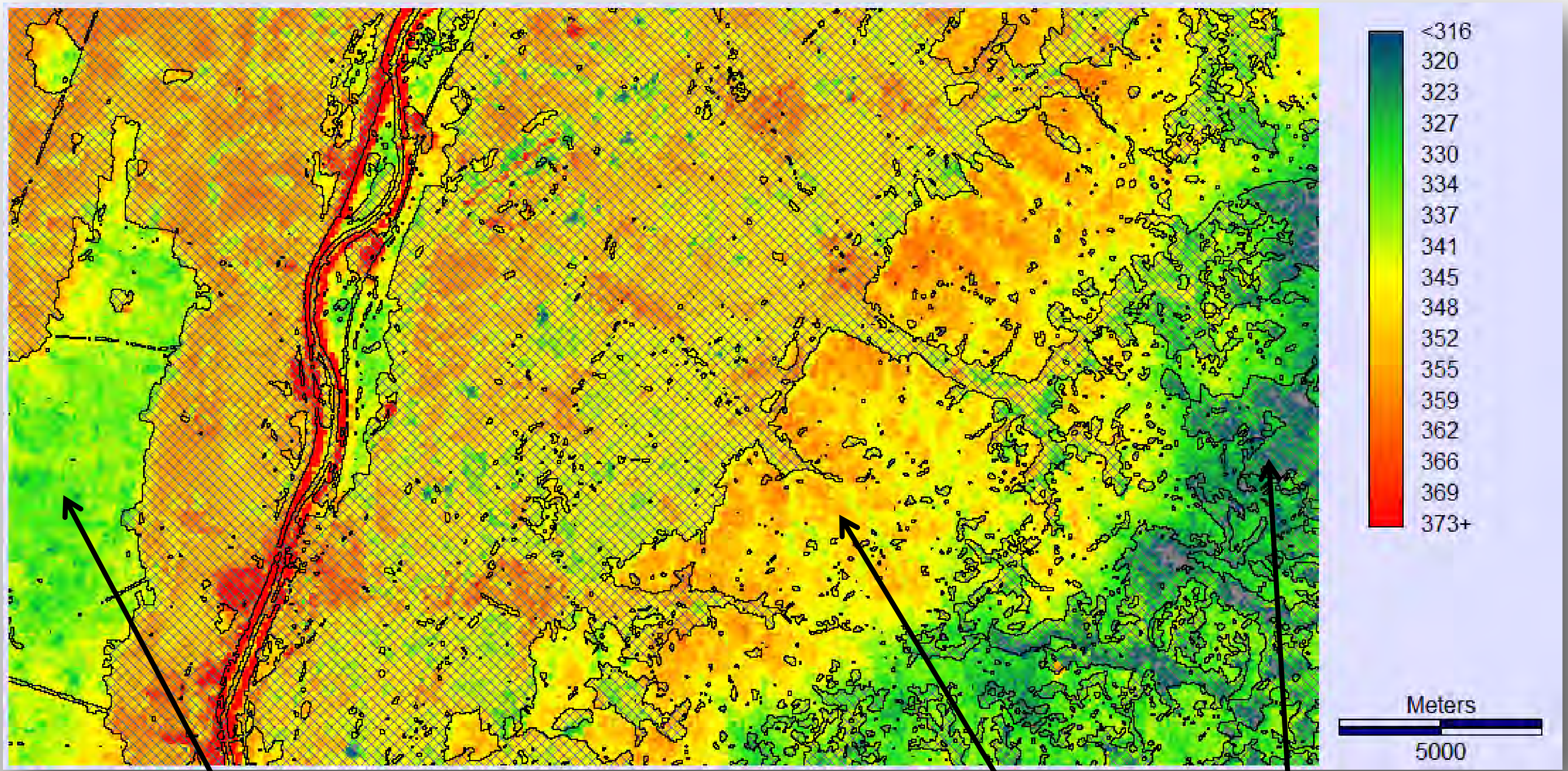


Aster Night LW-emission and LULC





Aster Night LW-emission of forest areas

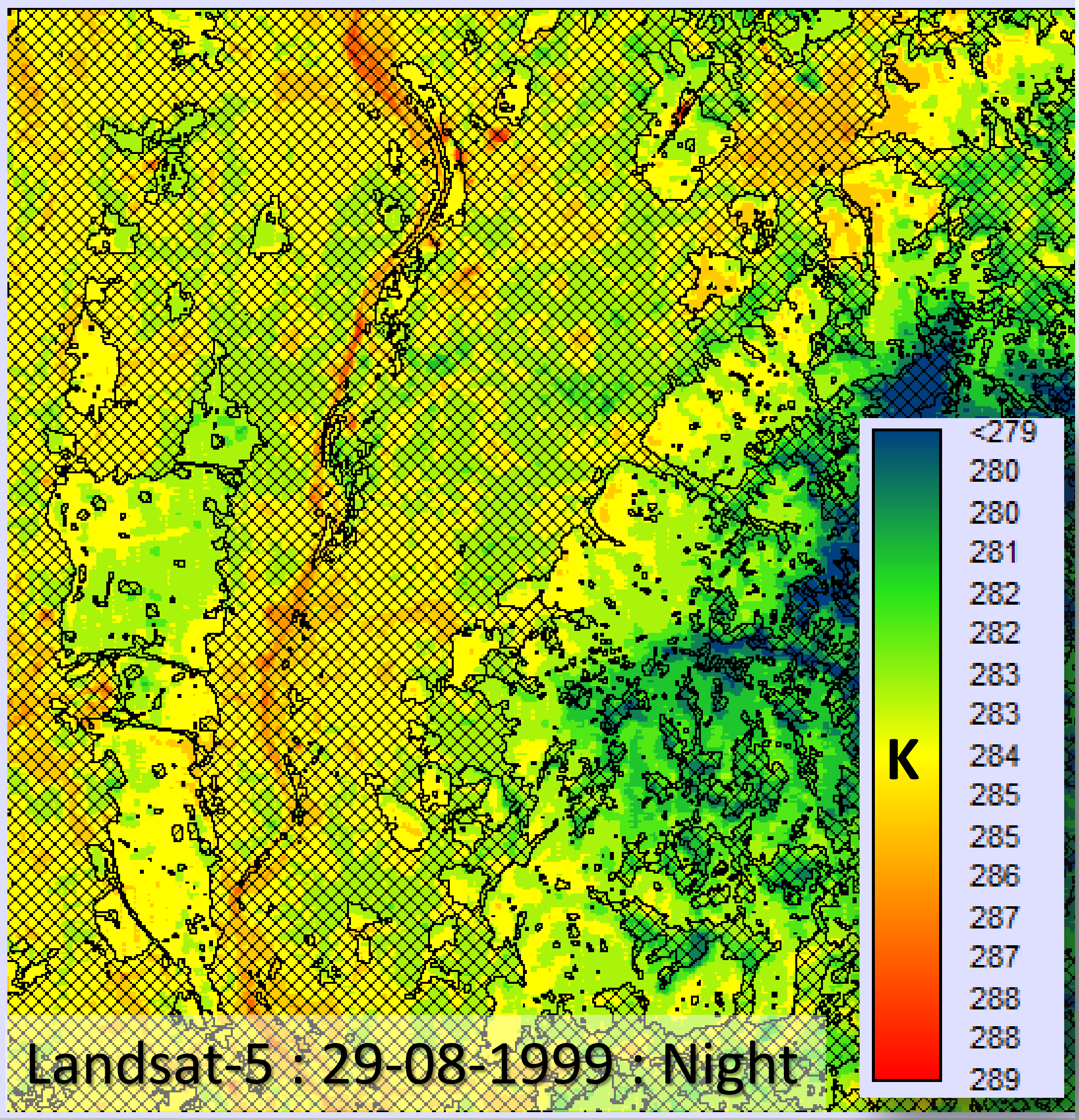


Forests at the lowlands of Rhine Valley : cool

Forest at the western slopes : warm

Forests at the high mountains : cool

Landsat Night-T_s of SW-Black Forest (in Kelvin)

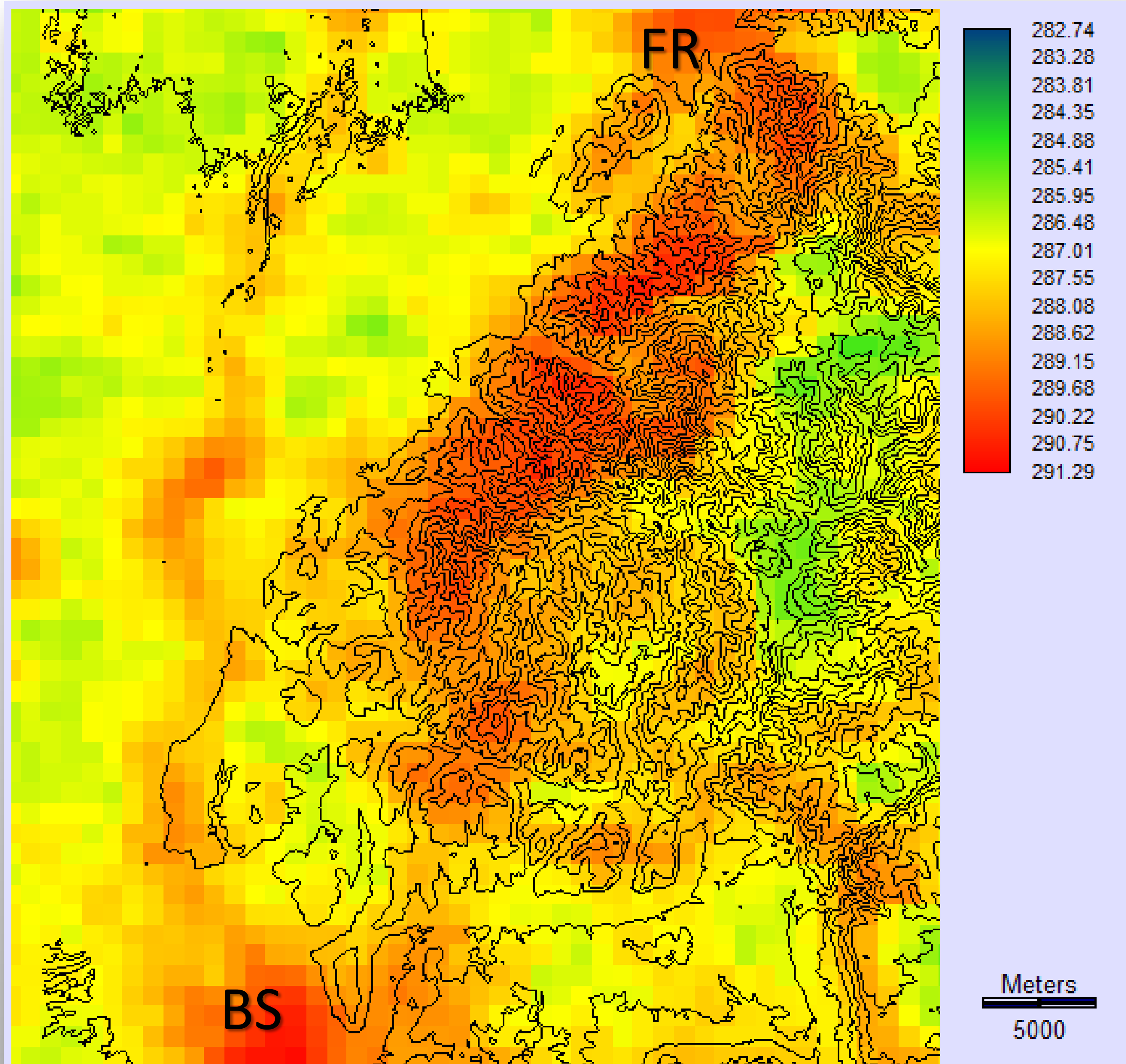


Net radiation at <u>nighttime</u>:

$Q^* = LW\downarrow - LW\uparrow$

$= LW\downarrow - \sigma\varepsilon T_s^4$

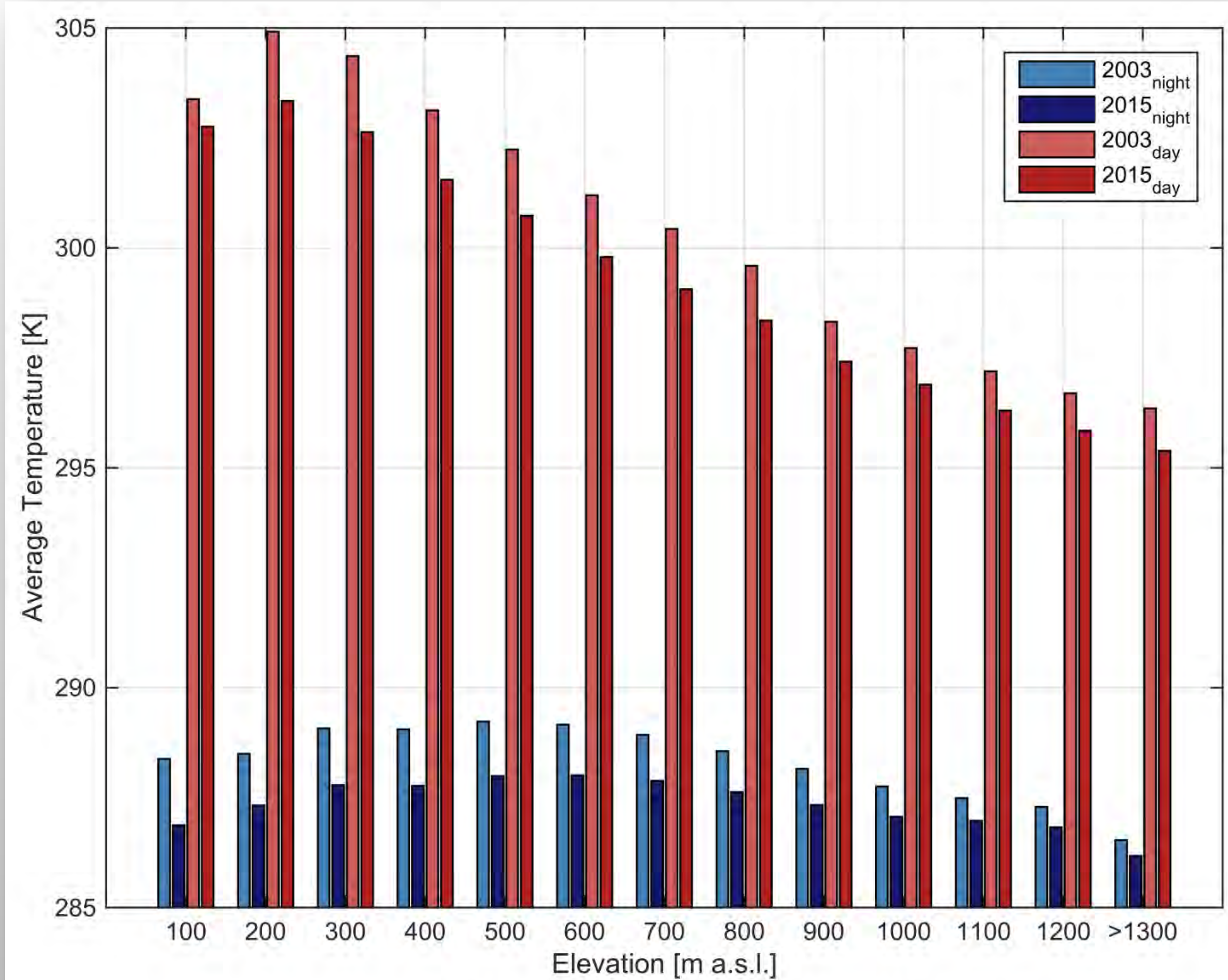
- $LW\downarrow < LW\uparrow$
- High T_{surf} on slopes
- Therefore very negative Q^* at high T_s.
- Q^* must be compensated by heat fluxes over whole night !
- What is the process ?



MODIS mean night emission from 40-65 cloudfree scenes during summer 2015

The highest emissions come from forests at slope sites !

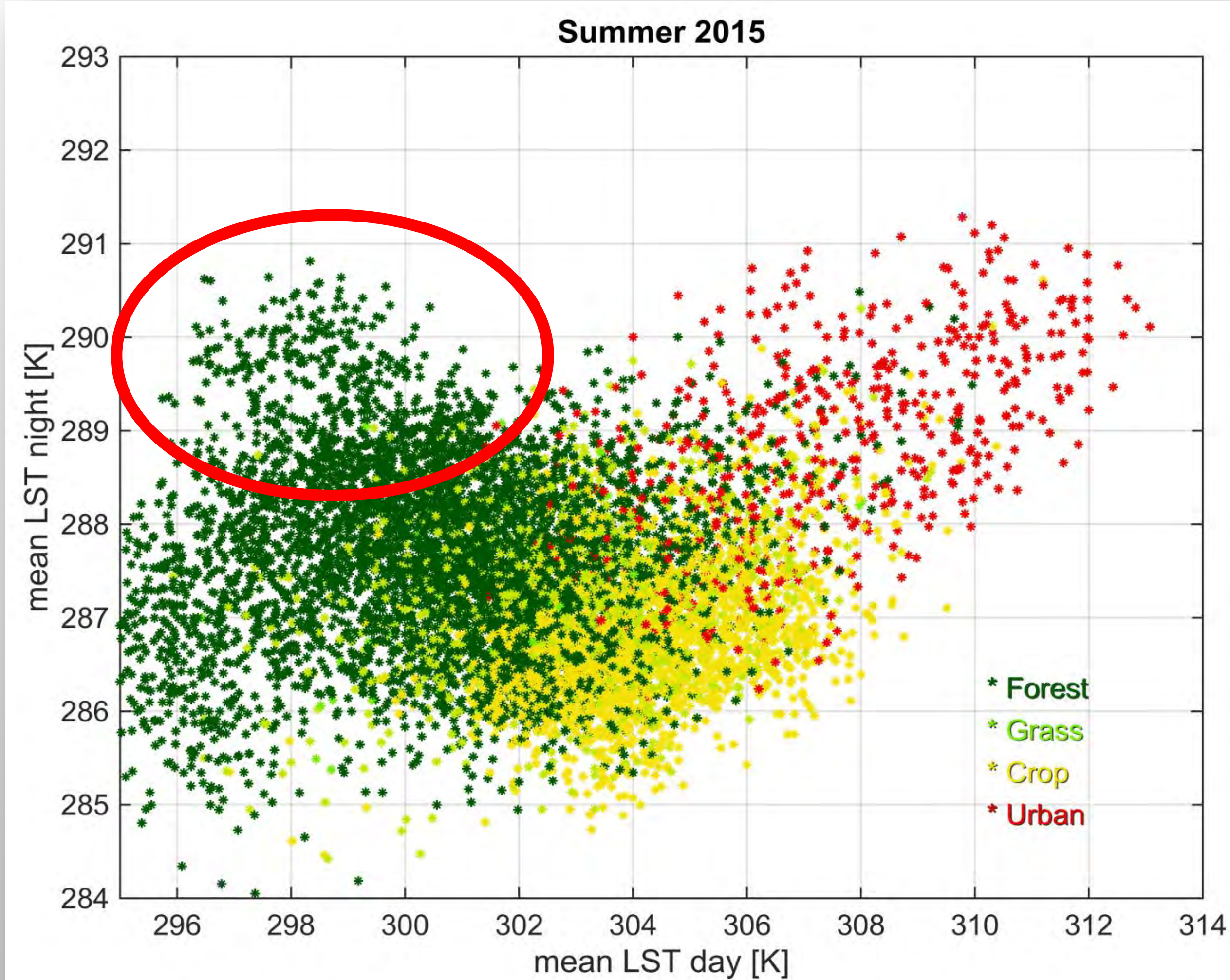
MODIS mean day/night emission as f(elevation)



During daytime surface temperature decreases with altitude.

During night time highest surface temperatures at 400 – 700 m altitude

MODIS mean day/night emission as f(LULC)



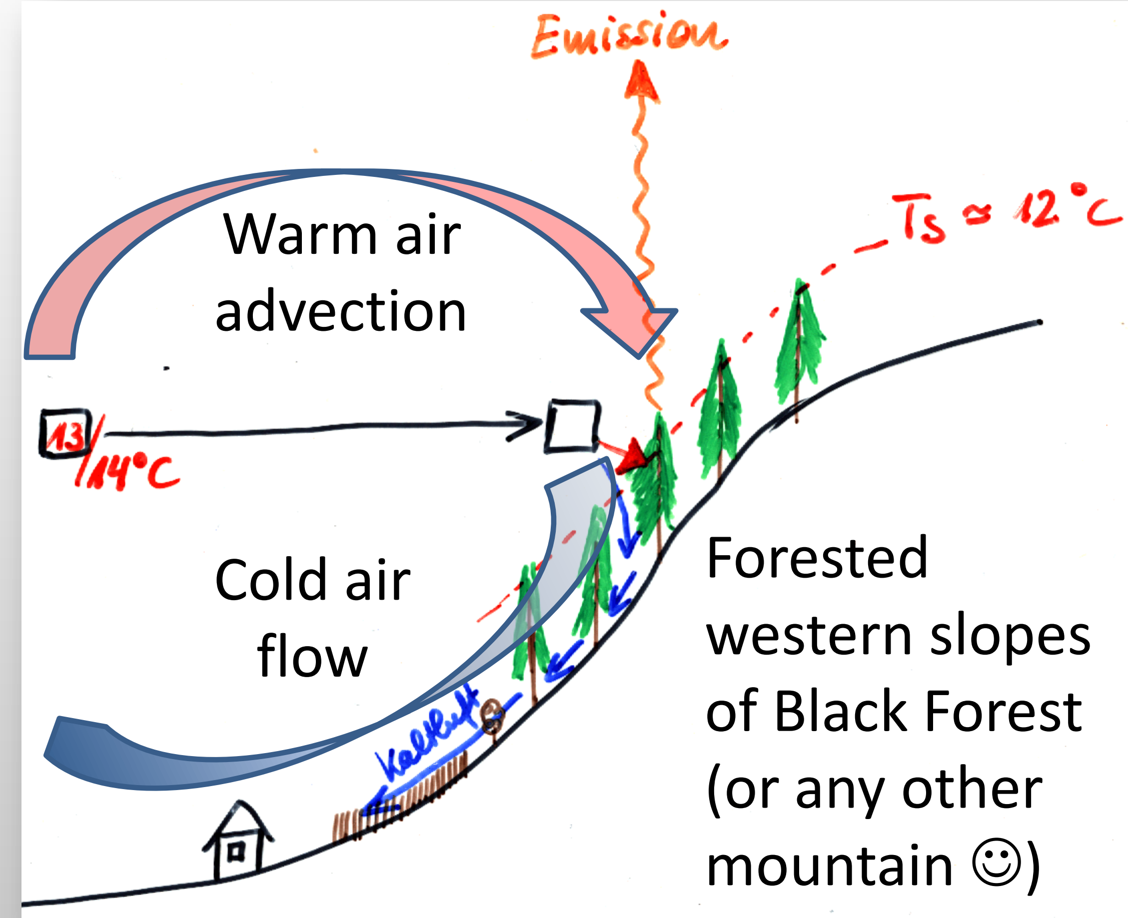
During day and night time urban areas show up highest surface temperatures.

Forests reach similar surface temperatures during night time as urban surfaces! These warm forest pixels at night are all at slope sites.

The problem : all night high surface temperatures

- Along the western slopes of the Black Forest at medium altitude and at probably all forested slopes around the world there are quite high T_s during night time.
- This feature can be detected all over the night and using various satellite sensors like Aster, Landsat, Modis etc. !
- The high surface temperatures imply a very negative net radiation of – 50 to – 100 Wm^2.
- This energy loss has to be compensated instantaneously by the heat fluxes (sensible and/or latent and/or storage heat flux).
- Which meteorological process is able to compensate negative Q* all over the night ?
- Which heat fluxes is responsible and how does the process work ?

Basic scheme of cold air production on slopes



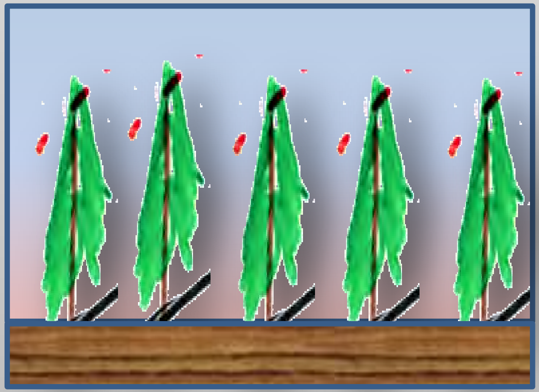
- Advection of slightly warmer air aloft from Upper Rhine Valley towards forest surface
- Heat transfer (sensible heat flux) to crown surface to compensate negative Q*
- This keeps LST high
- Energy loss of air means cooling of air
- Cooled air sinks down into trunk space and generates mountain wind system. This process runs all over the night!!
- Cold air production rate of forests ≈ 40 – 50 $m^3m^{-2}h^{-1}$ (vs 10 – 15 $m^3m^{-2}h^{-1}$ of grasland)

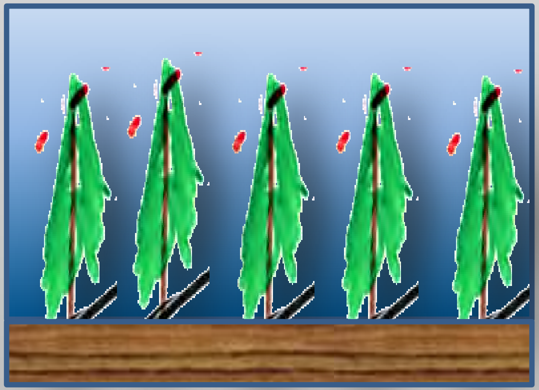
What happens at forest stands in the lowlands ?

Daytime
LST are cool due to evapotranspiration of trees during daytime. Net radiation is high due to cool surface and low albedo.

Early evening
When net radiation switches to negative values forest starts cold air production but tree canopies remain some time aloft the cold air pond.

Later at night
After some hours much cold air is produced which cannot flow off. Forest is steadily drowned in its cold air pond up to canopy height and above.





Conclusions

- Thermal IR imagery is an important spatially distributed information – not only during daytime
- But it is only one variable of the complex radiation and heat budget equations and all the other variables have to be considered
- The simple analysis of IR imagery alone leads mostly to erroneous interpretations and does not consider the complexity of heat flux processes
- In mountain areas the high surface temperatures of forested areas on slopes are indicating the cold air production and generation of mountain wind systems by a complex warm air mass advection – heat exchange process.
- During night time it is important to keep in mind that warm areas have a very negative net radiation which has to be compensated by heat fluxes. Only the sensible heat flux is able to compensate negative net radiation over the whole night. But this process generates cool air !

Conclusions

- If forests are in flat terrain then they are drowned by the cold air after some few hours and then surface temperatures are much colder
- There is much scientific work to be done in thermal IR data analysis to understand the complex heat flux processes – especially with night IR imagery
- Therefore it is very good to have night Landsat/Aster-thermal data available as a standard product
- This will generate important insights into boundary layer energy and heat flux processes.

Lessons learned : !?!?!?

High surface temperatures of forests at slope conditions during night time indicate their cold air production and the triggering of mountain valley wind systems !!!

This sounds crazy – but ….

keeping in mind the complete energy balance it is physically correct and can be validated by field measurements ….

Rome/Frascati area: Landsat-day-IR/Aster night-IR