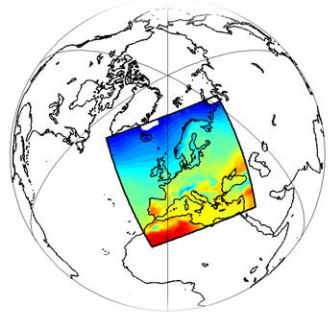
How to use climate models and building simulation to assess the impact of climate change on historic buildings and art collections?

ww.climateforculture.eu
Grant agreement No. 22 6973 (2009 - 2014)





OEDD Conference *Facing the challenge*
Athens 21 June 2019
Johanna Leissner, Fraunhofer Brussels
Johanna.Leissner@zv.fraunhofer.de

This project has received funding from the European Union's Seventh Framework Programme for research, technological development and demonstration under grant agreement No. 226973

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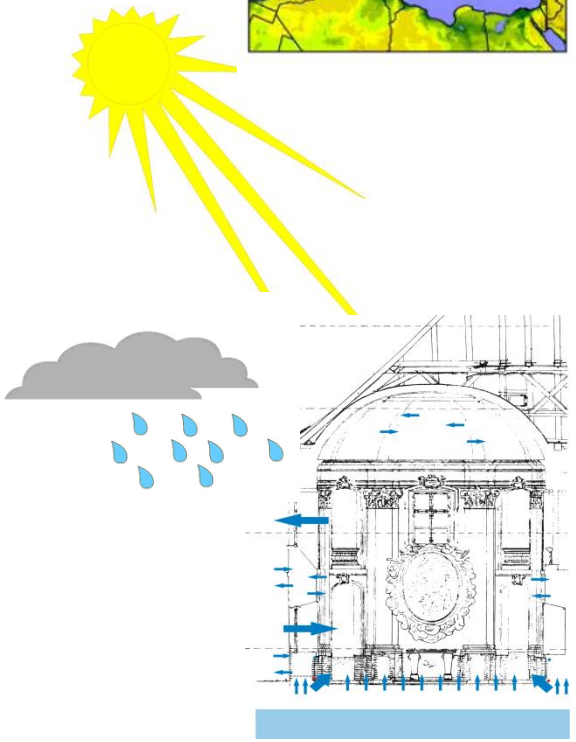
Scope of the project

- **High resolution outdoor and indoor climate modelling on a regional scale**
- **Development of hygrothermal whole building simulation software for historic buildings**
- **Case studies database and stakeholder contributions**
- **Onsite T/rH measurements and experimental monitoring with DHSPI (direct impact), 3D microscope, radiellos, free water sensor and glass sensors**
- **Adaptation, mitigation and energy efficiency measures**
- **Socio-economic report on cost-benefits**
- **Strong interdisciplinary and multidisciplinary training and education curriculum**



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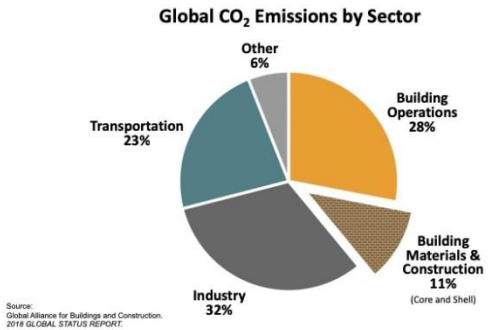
Focus on gradual changes not extreme events – request by European Commission

Focus on future indoor climate – because many of our cultural heritage is displayed and stored inside buildings – reference to Recommendation of Council of Europe 2018!

Quality of indoor climate is important factor for preservation of cultural heritage

Indoor climate control is very costly and requires a large amount of energy!!!

Buildings are responsible for one quarter of total energy consumption and greenhouse gas emissions according to Eurostat.



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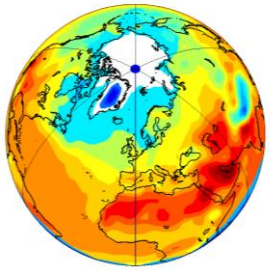
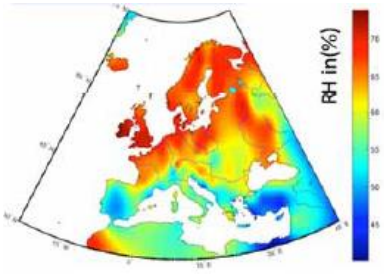
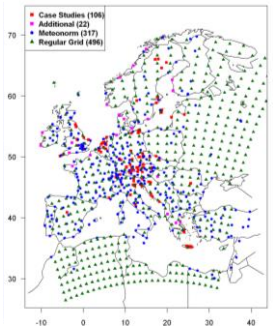
Climate for Culture

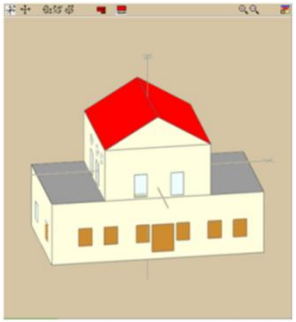
Climate for Culture – methodology





2100
?





→ 55,650 climate maps and risk maps

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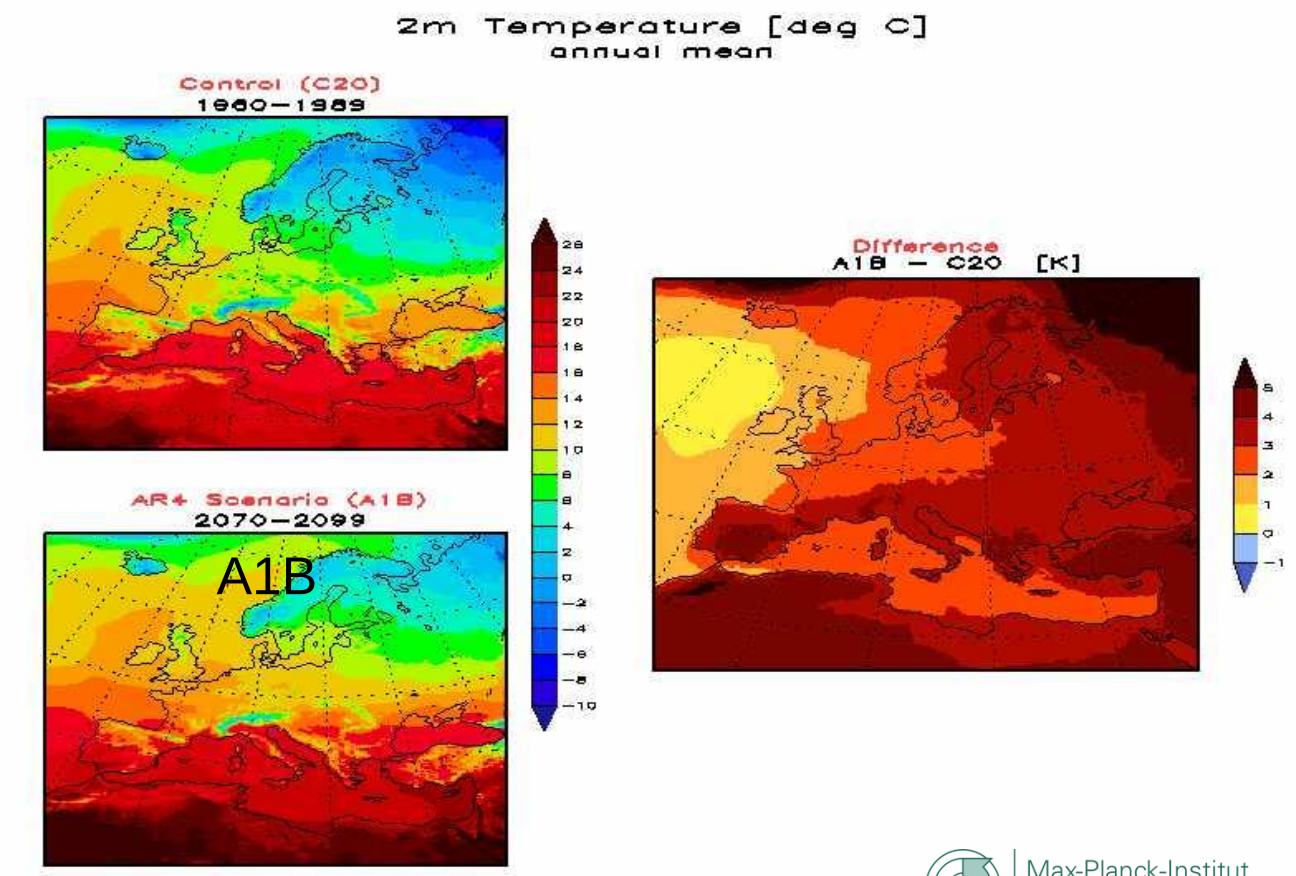
REMO climate modelling - two moderate IPCC emission scenarios – A1B and RCP4.5

Assumptions

- **rapid economic growth**
- **increasing global population until 2050, decline after 2050**
- **rapid introduction of new and more efficient technologies**
- **balanced energy sources**



Max-Planck-Institut für Meteorologie

ENSEMBLES project (http://ensembles-eu.metoffice.com)

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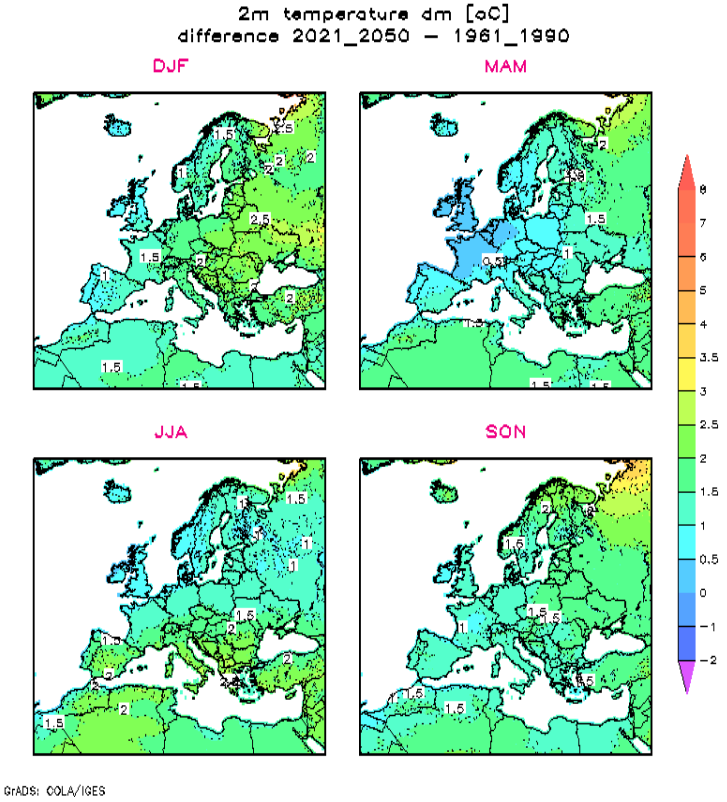
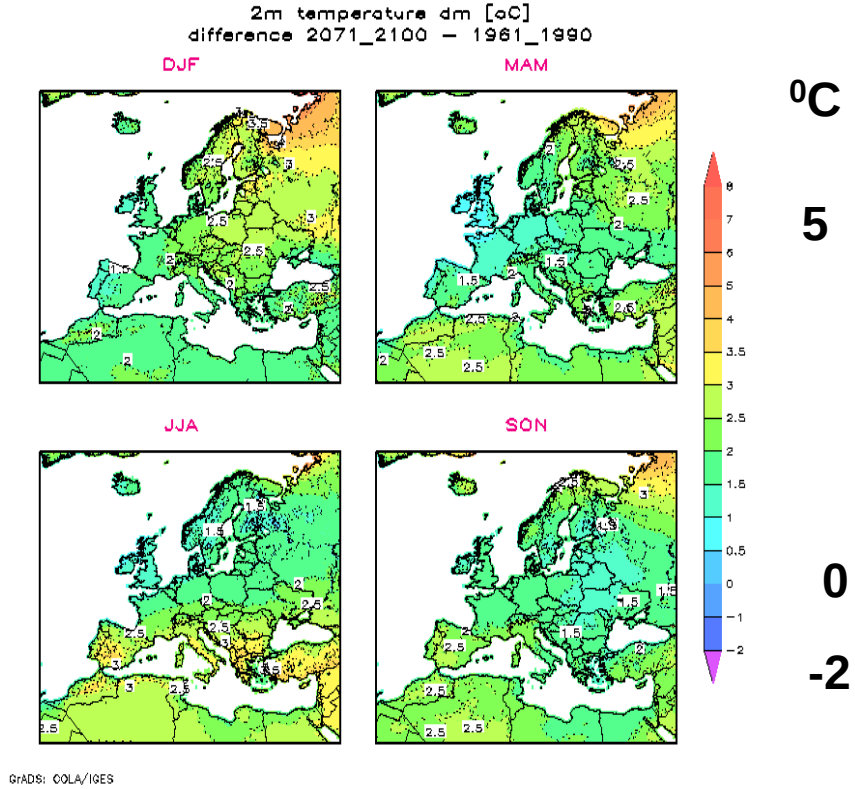
Climate simulation: Temperature

30-year seasonal mean changes for the moderate emission scenario relative to 1961 – 1990; Change in temperature 2m above sea level



2021-2050



2071-2100

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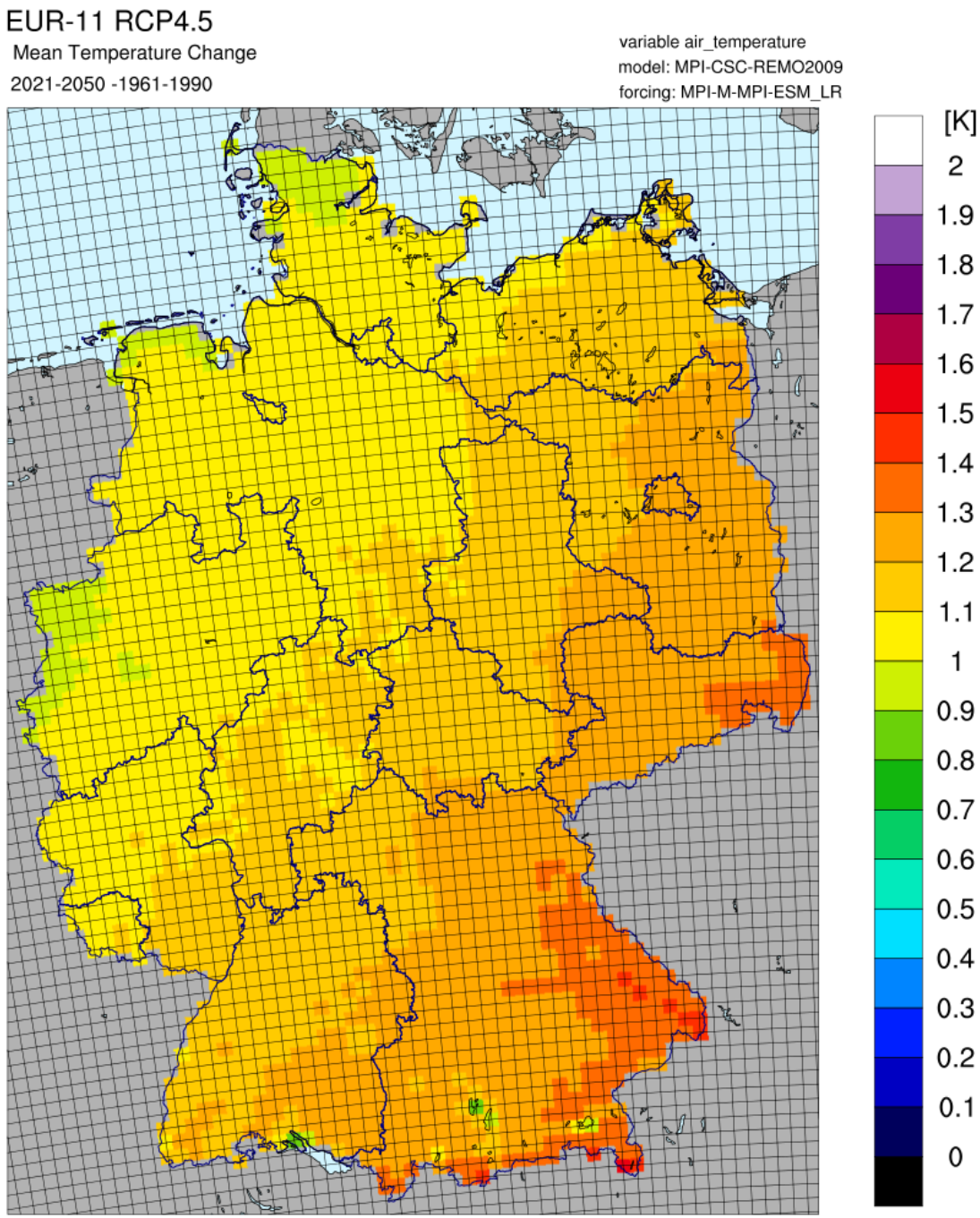
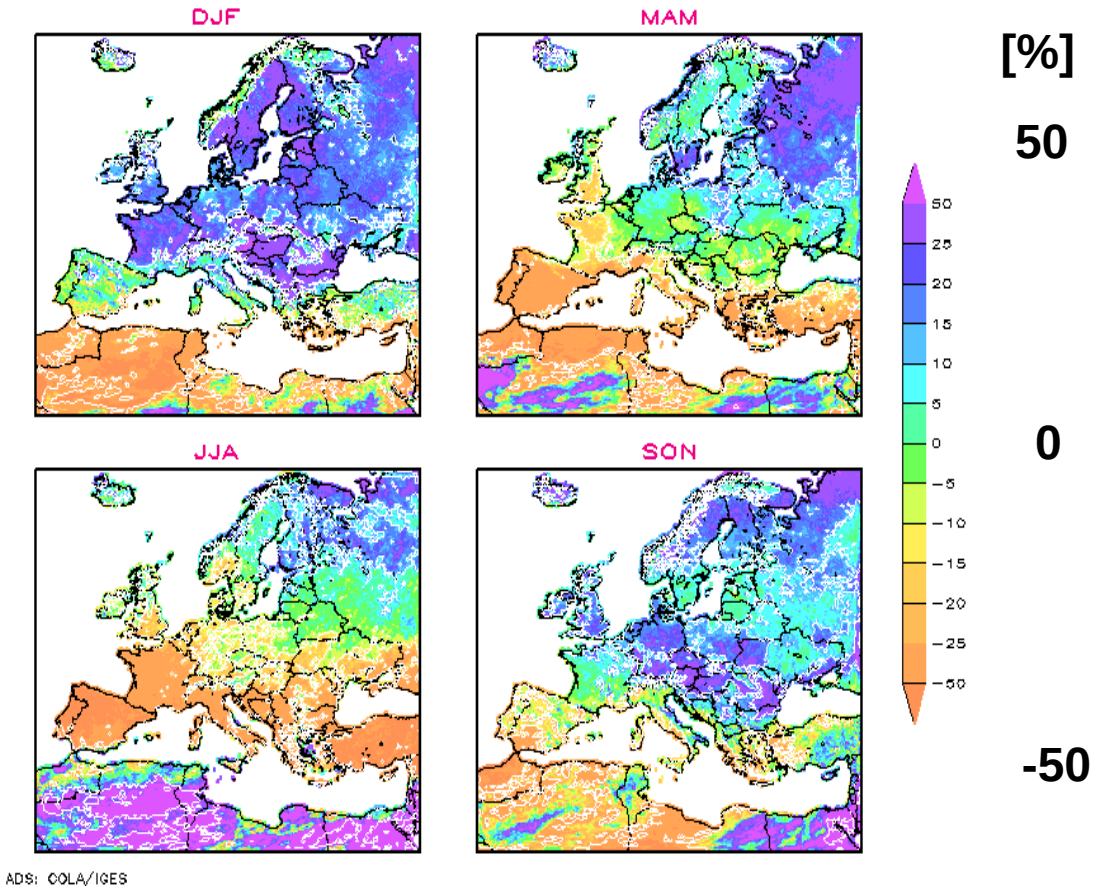

EUR-11 RCP4.5
Mean Temperature Change
2021-2050 -1961-1990
variable air_temperature
model: MPI-CSC-REMO2009
forcing: MPI-M-MPI-ESM_LR
[K]
2
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0

Climate simulation: Precipitation

30-year seasonal mean changes for the moderate emission scenario 2071 – 2100 relative to 1961 – 1990



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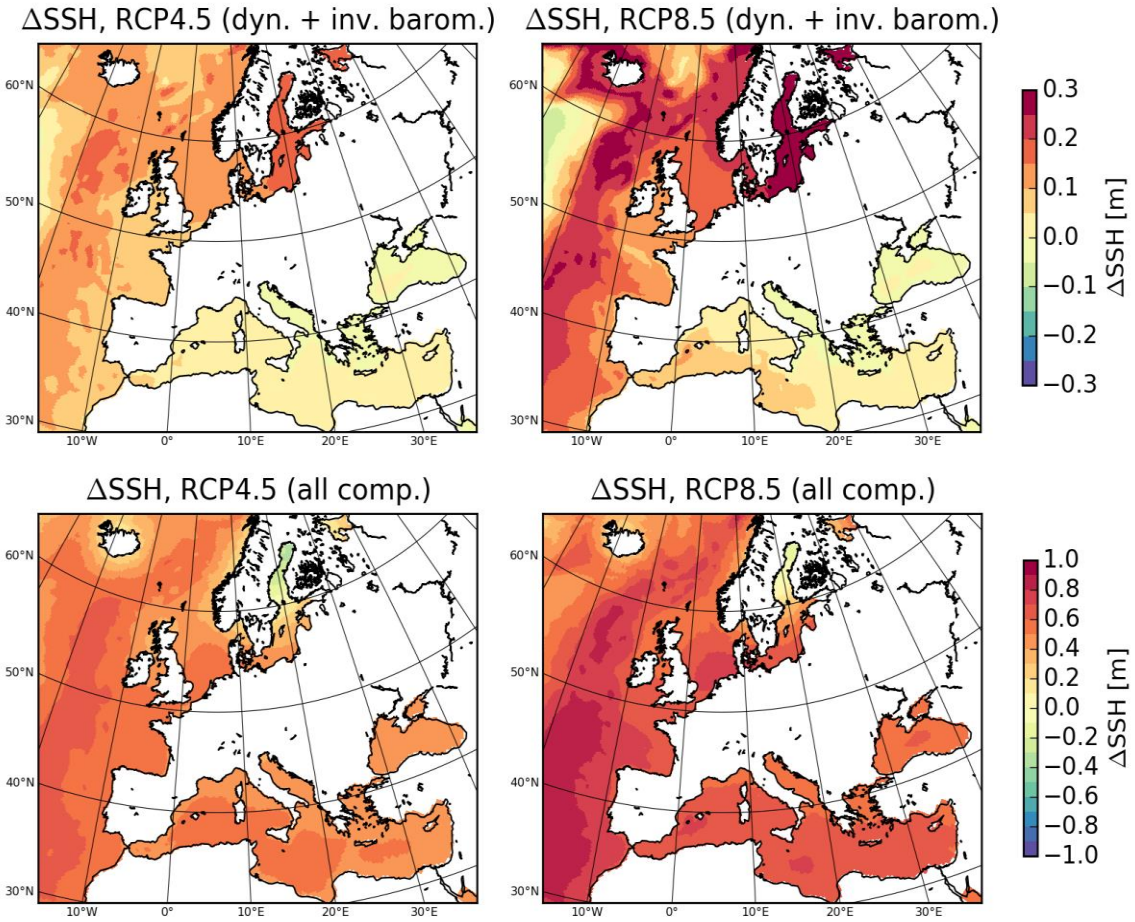
Climate simulation : Sea Level Rise

Changes in sea level rise, [m] (2081-2100 relative to 1985-2005) for different emission scenarios RCP4.5 and RCP8.5



Sources:
Mathis M, Mikolajewich U. et al. (2018), under revision

IPCC AR5. Church et al. (2013) in Sea level change, in Climate Change 2013: The Physical Science Basis,

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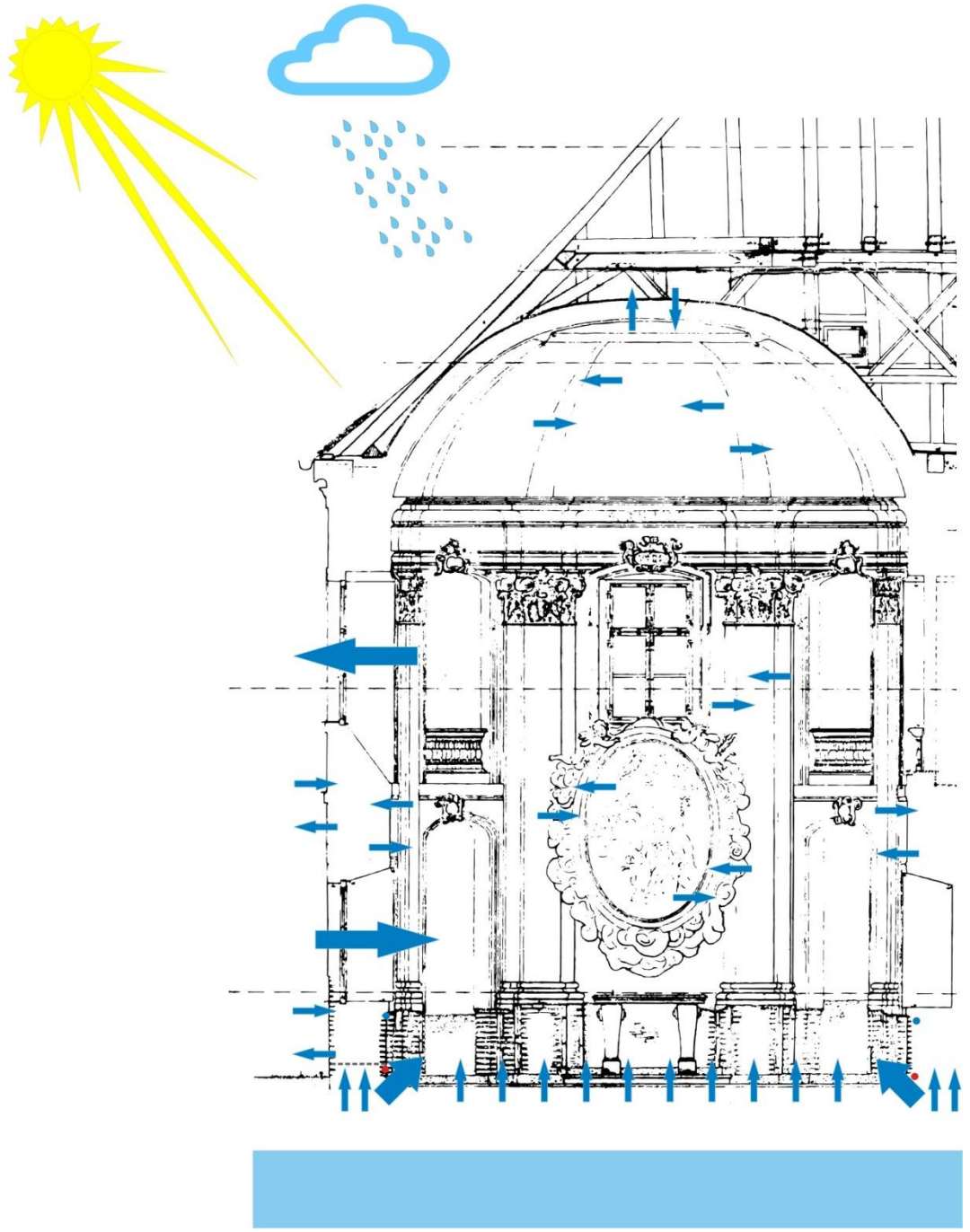
Influences on the indoor environment

- Outdoor climate!
- Visitors / use
- HVAC systems
- Ventilation / outdoor infiltration
- Heat buffering
- Moisture / heat / pollution sources
- Moisture buffering

  (room / interior fittings)
- Solar gains



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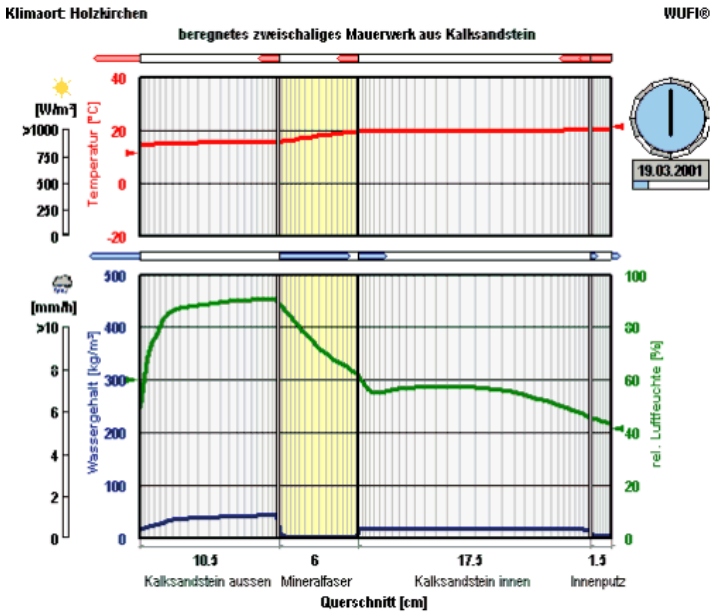
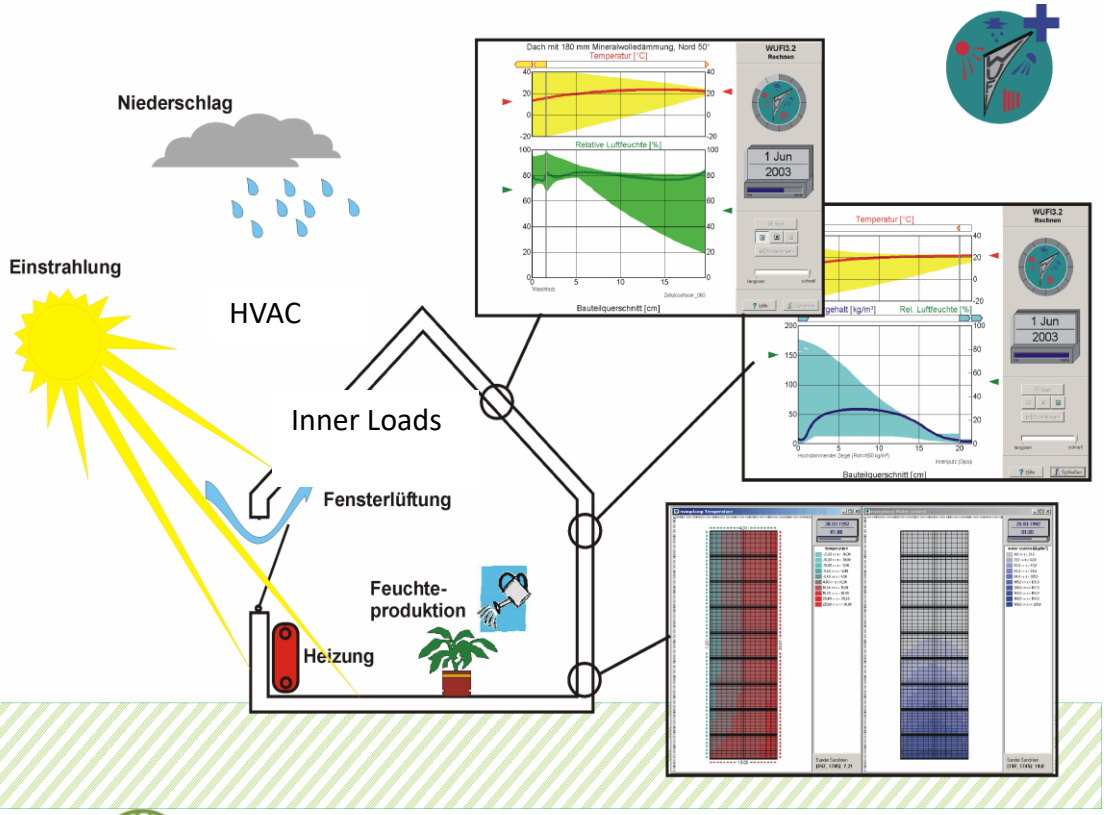
Modelling of buildings – from components to whole buildings





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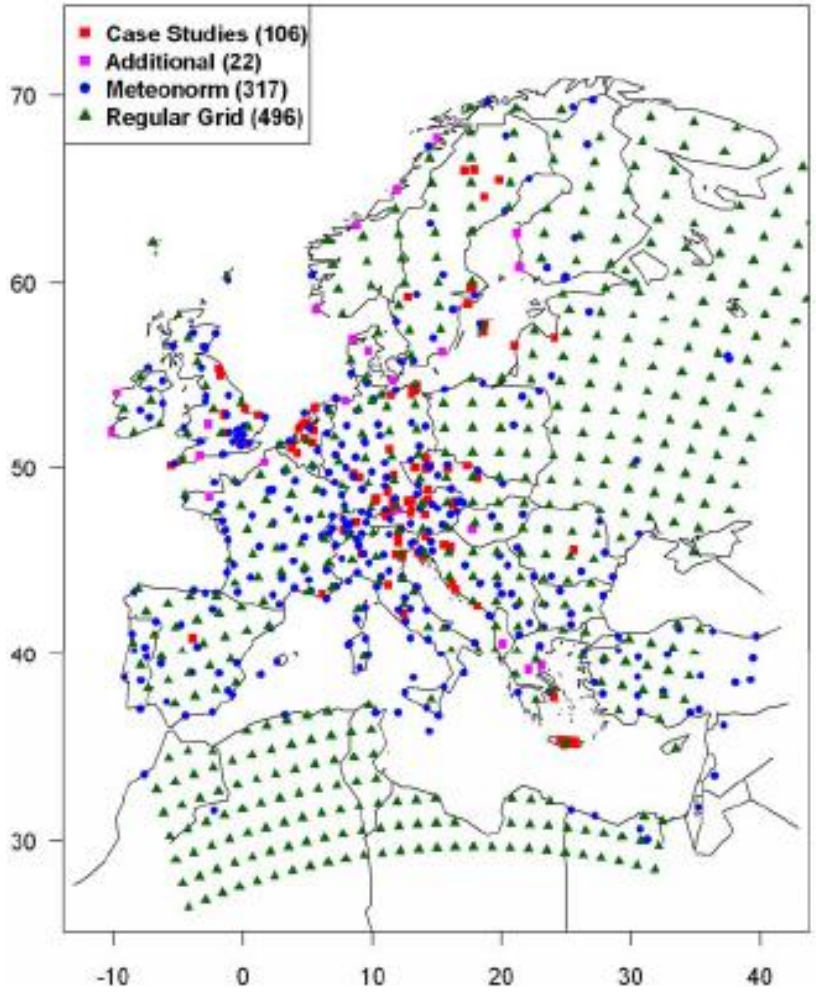
High resolution regional climate model and climate indices – for over 500 gridpoints with hourly resolution



Value		Unit
Temperature	TA	°C
Relative Humidity	HREL	%
Normal Rain	RN	mm
Wind Speed	WS	m/s
Wind Direction	WD	degree
Global Radiation	ISGH	W/m2
Diffuse Radiation	ISD	W/m2
Global Counterradiation	ILAH	W/m2
Cloud Coverage	CI	%
Ground temperature	GT	°C
Ground reflectance	GR	-
Air Pressure	PSTA	Pa

Plausibility and applicability of the complete datasets have been verified with past weather records

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What are the results from hygro-thermal whole building simulations?

- **Interior conditions**
  - Temperature
  - Relative Humidity
- **Surface and component layer conditions**
  - Temperature
  - Relative Humidity
  - Water Content
- **Energy Demand**
  - Heating / Cooling
  - Humidification / Dehumidification
- **Building Controls**
  - Ventilation
  - Heating

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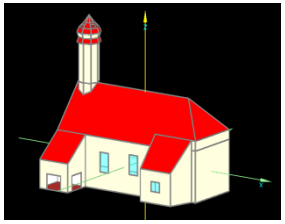
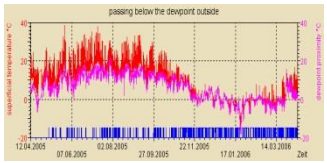
Risk assessment methodology

Measurement,
Direct impact!



Simulation



Weather & Climate predictions

$$\dot{x}(t) = A\,x(t) + B\,u(t),$$
$$y(t) = C\,x(t) + D\,u(t).$$

Transfer Functions

Indoor Climate

Energy Demand

Risk Assessment

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Examples for Indoor Climate and Risk Assessment

Indoor Climate	• Temperature • Humidity including fluctuations
Biological Damage	• Mould Growth • Insect Degree Days
Chemical Damage	• Lifetime Multiplier: Paper & Silk • Degradation of Photographs
Mechanical Damage	• Wooden Objects • Salt Crystallization Cycles

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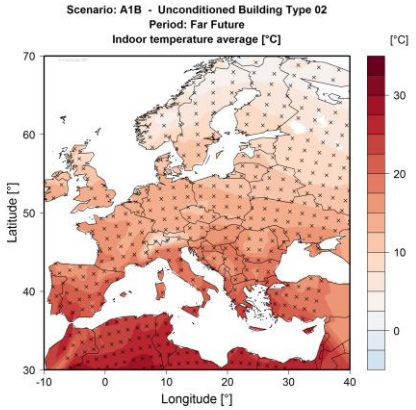
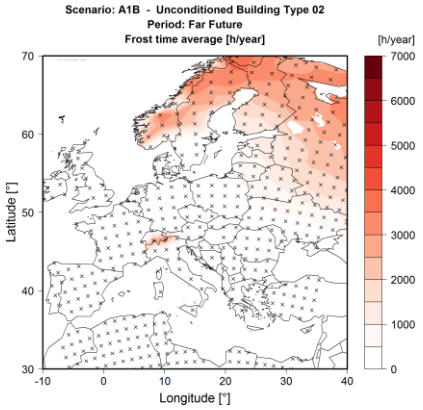
What kind of map plots have been created?

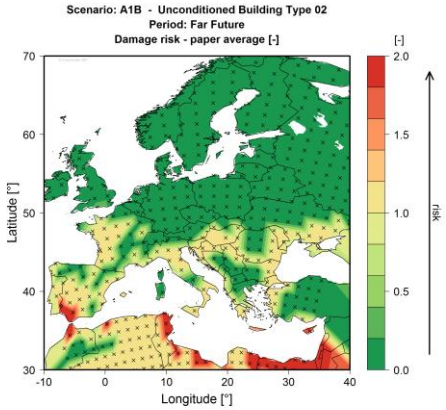
Indoor Climate

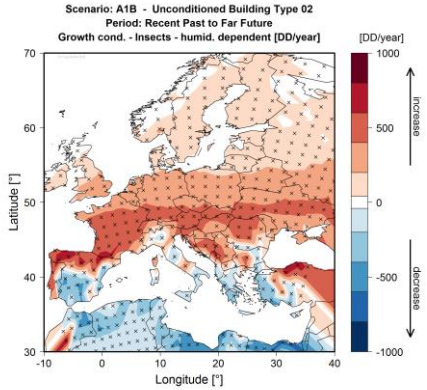




Damage Functions

Risk Categories





Differences between Periods

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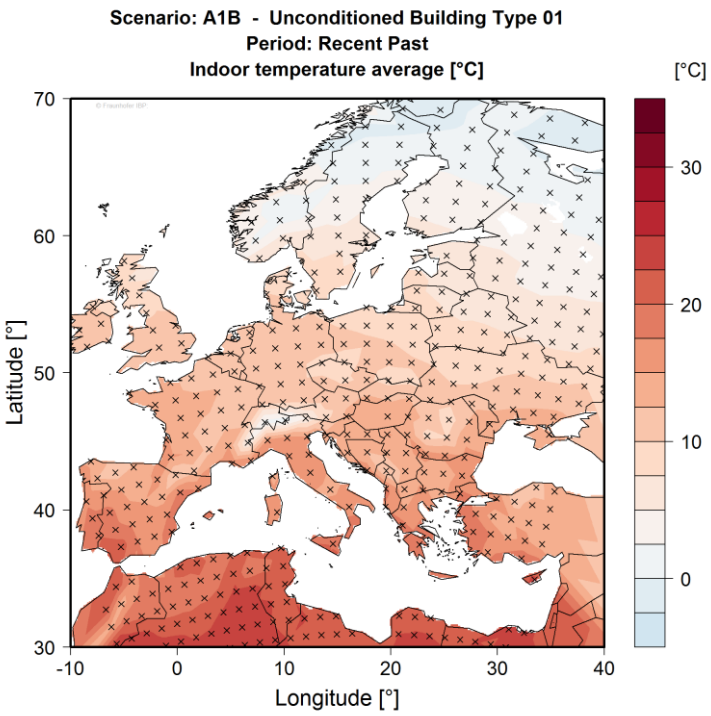
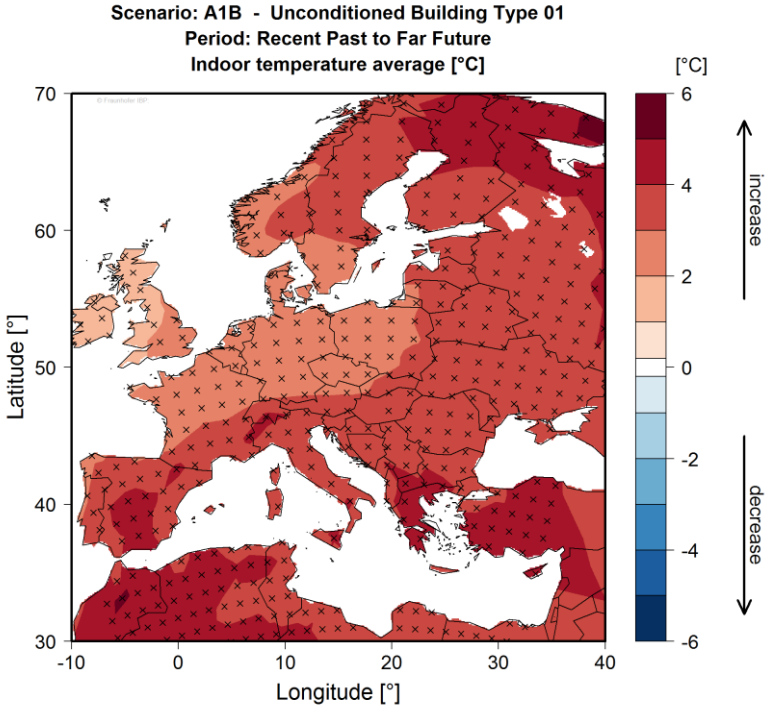
Mean Indoor Temperature – moderate scenario

Recent Past (1960 – 1990)



Difference to Far Future



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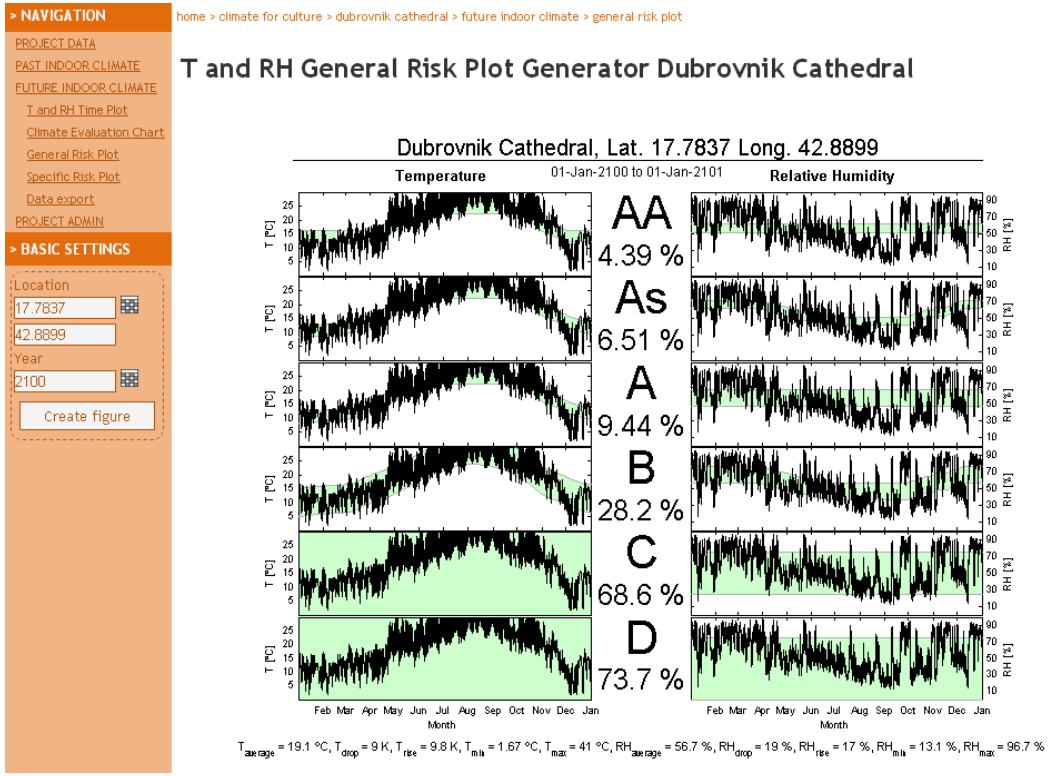
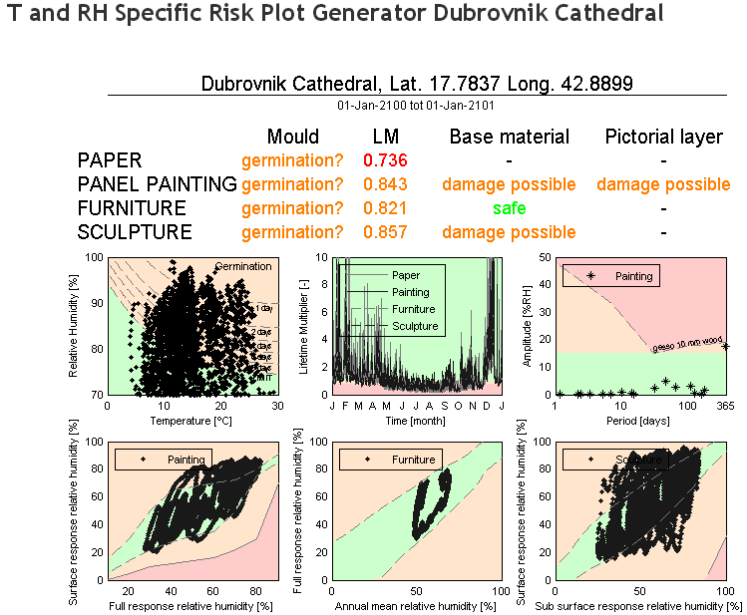
Example Dubrovnik Cathedral

Future indoor climates – 2100/2101





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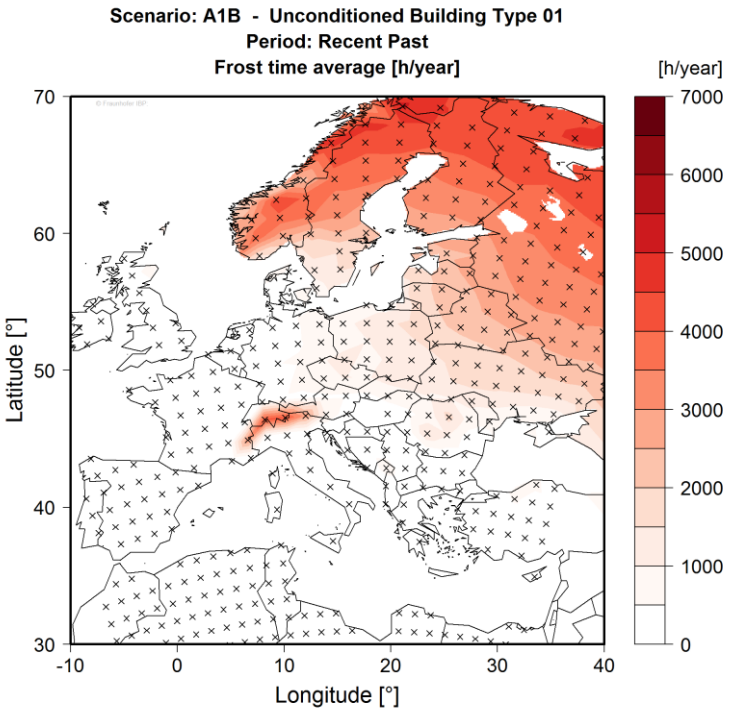
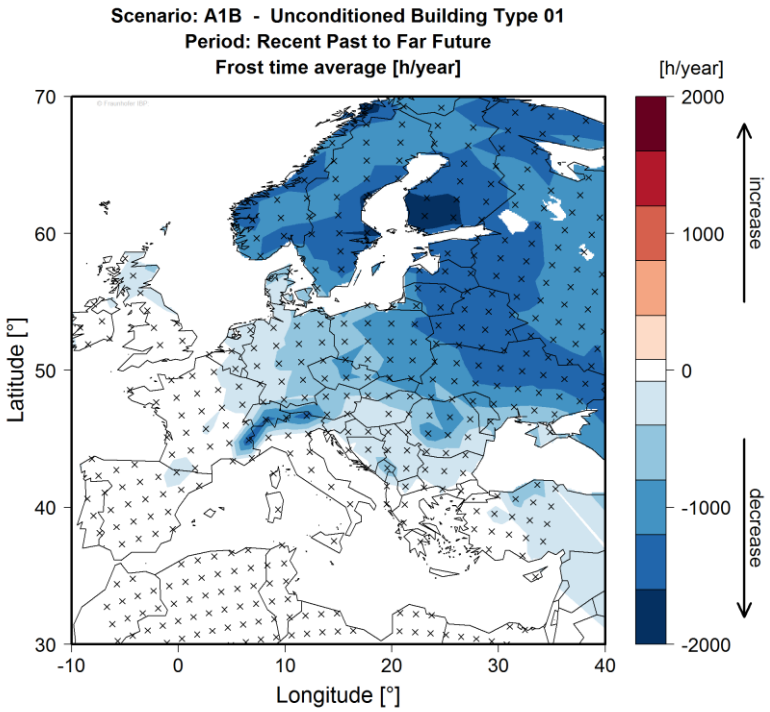
Average frost time – hours per year

Recent Past (1960 – 1990)



Difference to Far Future



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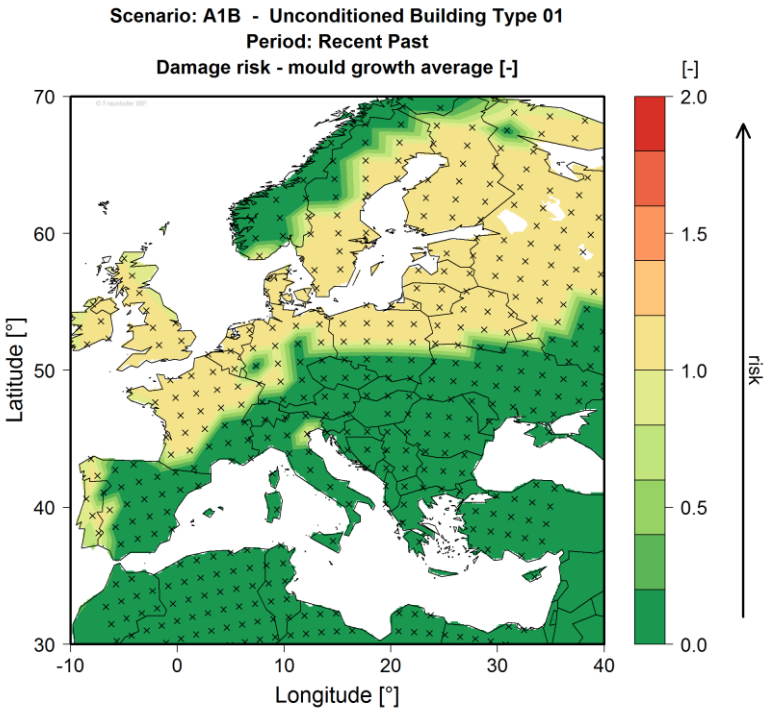
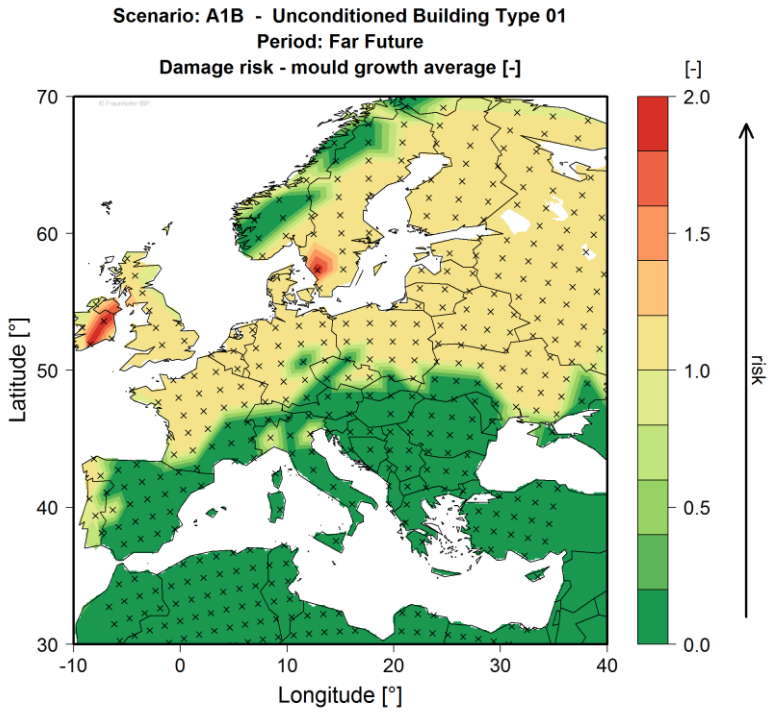
Mould Growth – an increasing danger

Recent Past (1960 – 1990)



Far Future (2070 – 2100)



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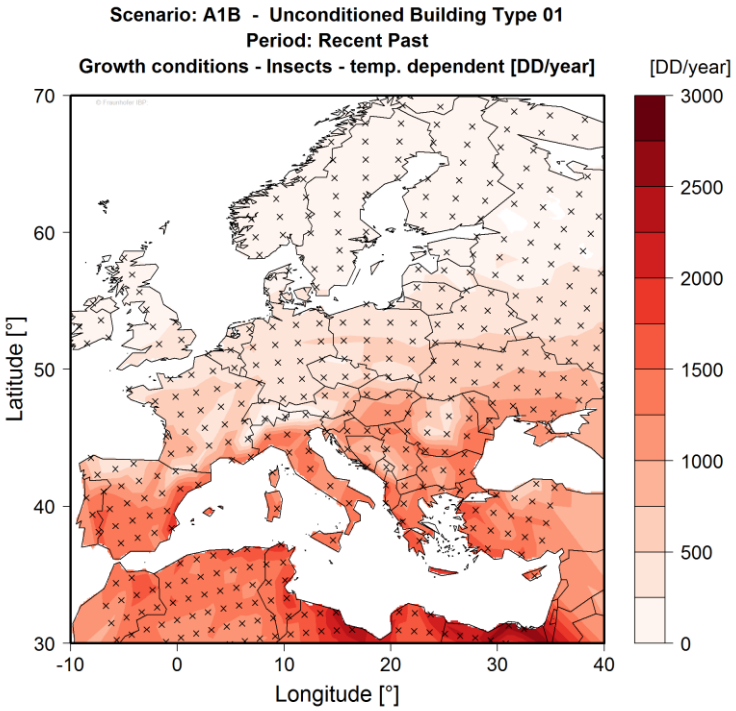
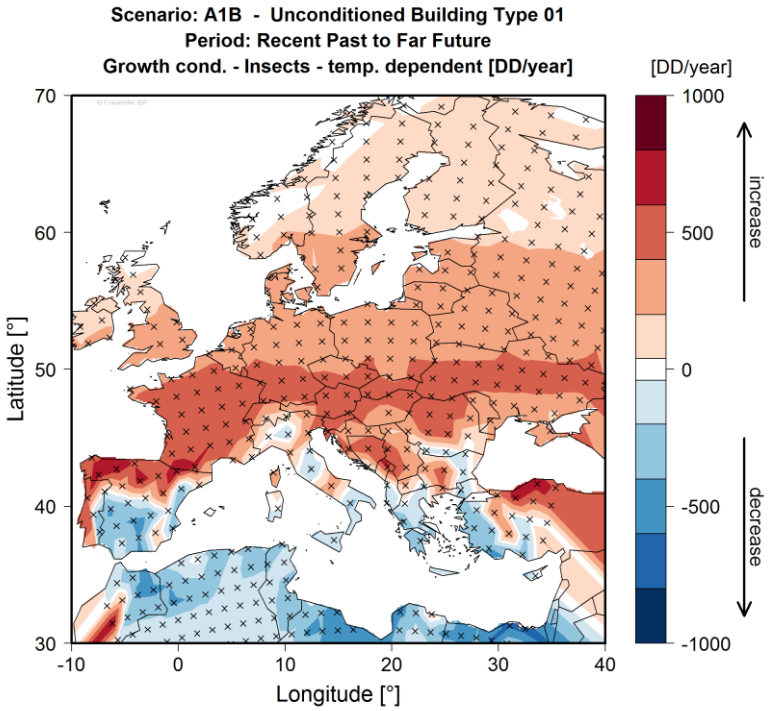
Insect Degree Days – more and more a problem

Recent Past (1960 – 1990)



Difference to Far Future



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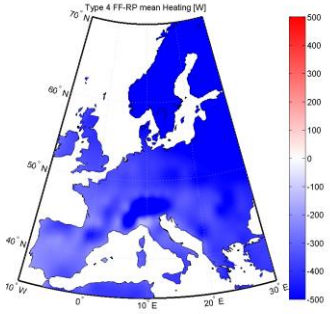
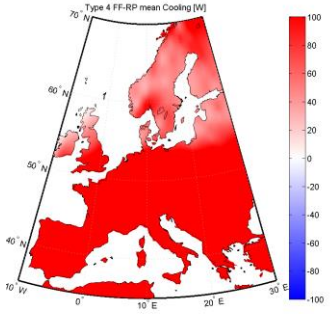
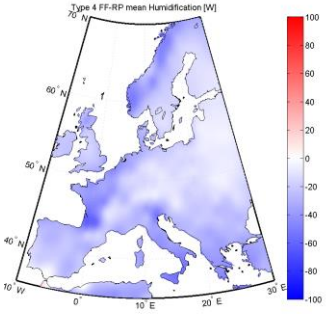
Future energy demand

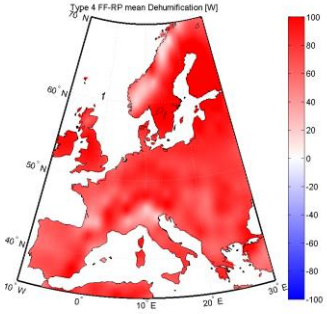
- changes from Recent Past to Far Future (A1B)

Heating + **Cooling** + **Humidification** + **Dehumidification**

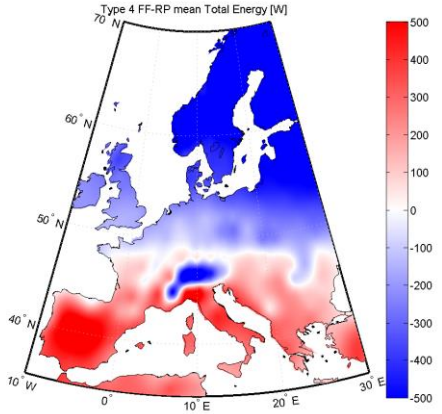


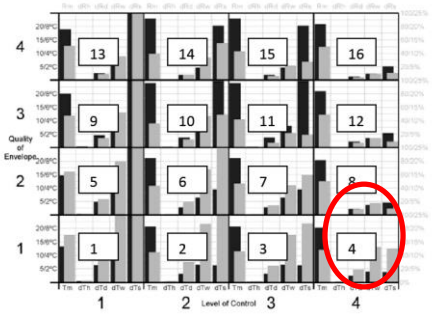






= **Total**





For a highly controlled building

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Climate for Culture

Climate for Culture methodologies already applied in

- **Trebon Castle** Archive (PLC control system in RH control) CZ
- **Karlstejn Castle** Great Tower (controlled ventilation system for RH control) CZ
- Various **historic buildings** of National Trust (UK) – conservation heating
- **Skokloster Castle** (Testing and cross-comparison of different control techniques) SE
- **Linderhof Castle** (Concept of ventilation system) DE
- **Church St. Bartholomä** (controlled ventilation system), DE
- **St. Renatus Chapel** (conservation heating control system) DE
- **Hofburg Vienna** (controlled ventilation through natural ventilation) AT
- **Academy of fine Arts**, Vienna (monitoring and evaluation of the earlier implementation of building control methods) AT
- **Museum of Fine Arts**, Vienna (installing of radiant tempering system) AT
- **Amerongen Castle** (heating system) NL

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Czech Technical University in Prague

UPPSALA UNIVERSITET

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3. **Consiglio Nazionale Delle Ricerche-Istituto di Scienze dell'atmosfera e del Clima, *Italy***
4. **University of Zagreb, *Croatia***
5. **Institute of Electronic Structure and Laser, IESL/FORTH, *Greece***
6. **Max Planck Institute for Meteorology, *Germany***
7. **Technische Universität München, *Germany***
8. **Eindhoven University of Technology, *Netherlands***
9. **University of Ljubljana, *Slovenia***
10. **Gradbeni Institut ZRMK, *Slovenia***
11. **Gotland University, *Sweden***
12. **Andreas Weiß, freelance conservator-restorer, *Germany***
13. **Engineering Consulting & Software Development, *Poland***
14. **Krah & Grote Measurement Solutions, *Germany***
15. **TB Käferhaus GmbH, *Austria***
16. **Haftcourt Ltd. *UK/Sweden***
17. **ACCIONA, S.A, *Spain***
18. **Bayerische Verwaltung der staatlichen Schlösser, Gärten und Seen, *Germany***
19. **Bayerische Staatsgemäldesammlungen – Doerner Institut, *Germany***
20. **National Trust for England, Wales and Northern Ireland, *UK***
21. **Kybertec Ltd., *Czech Republic***
22. **Glasgow Caledonian University, *UK***
23. **Center for Documentation of Cultural & Natural Heritage, *Egypt***
24. **Jonathan Ashley-Smith, Consultant for Conservation Risk Assessment, *UK***
25. **Institut National du Patrimoine, *France***
26. **London School of Economics & Political Science, *UK***
27. **Fondazione Salvatore Maugeri - Clinica del Lavoro e della Riabilitazione, *Italy***

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Climate for Culture

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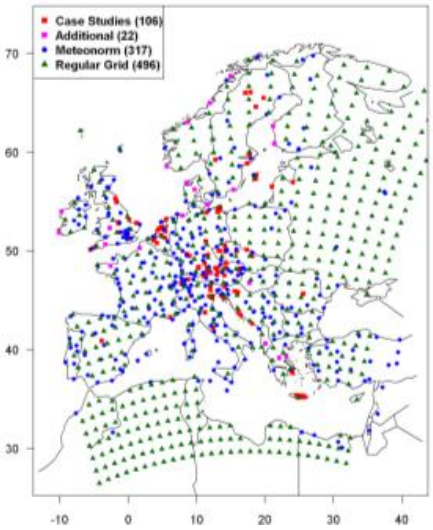
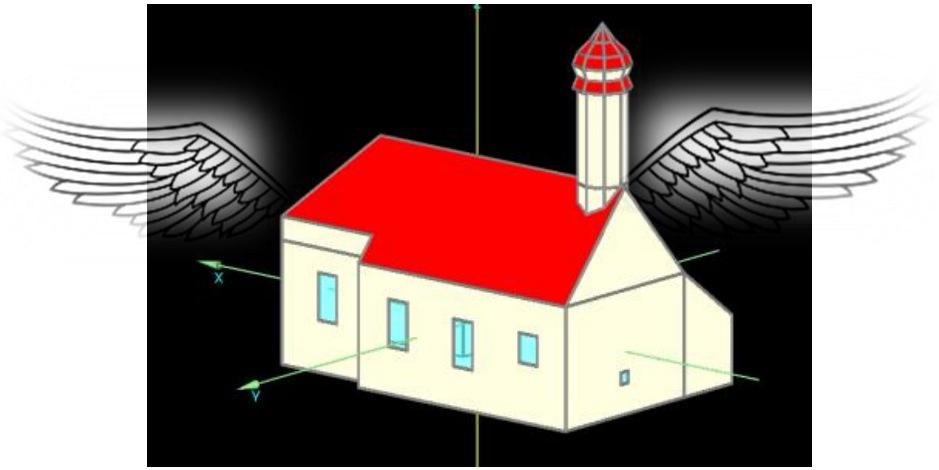
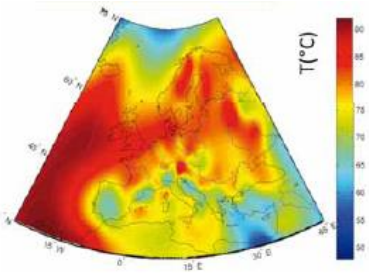
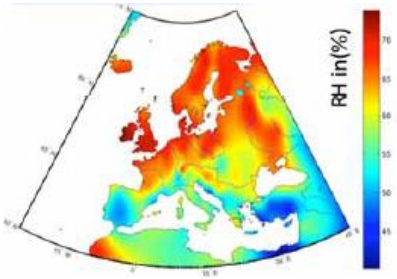
A historic building flying through time and space









Year 2012

Year 2100

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Reserve Folien!

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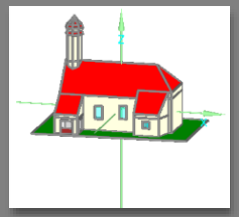
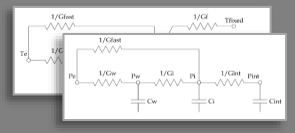
Climate for Culture

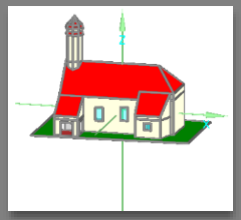
Procedure

Outdoor Climate

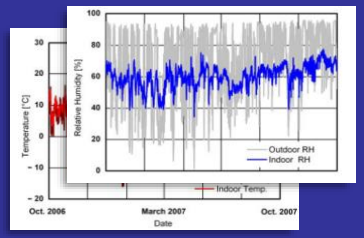
Indoor Climate



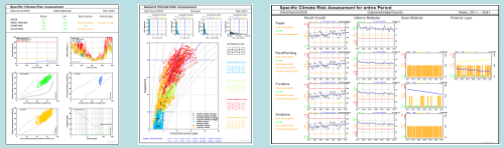




Effect of Indoor Climate

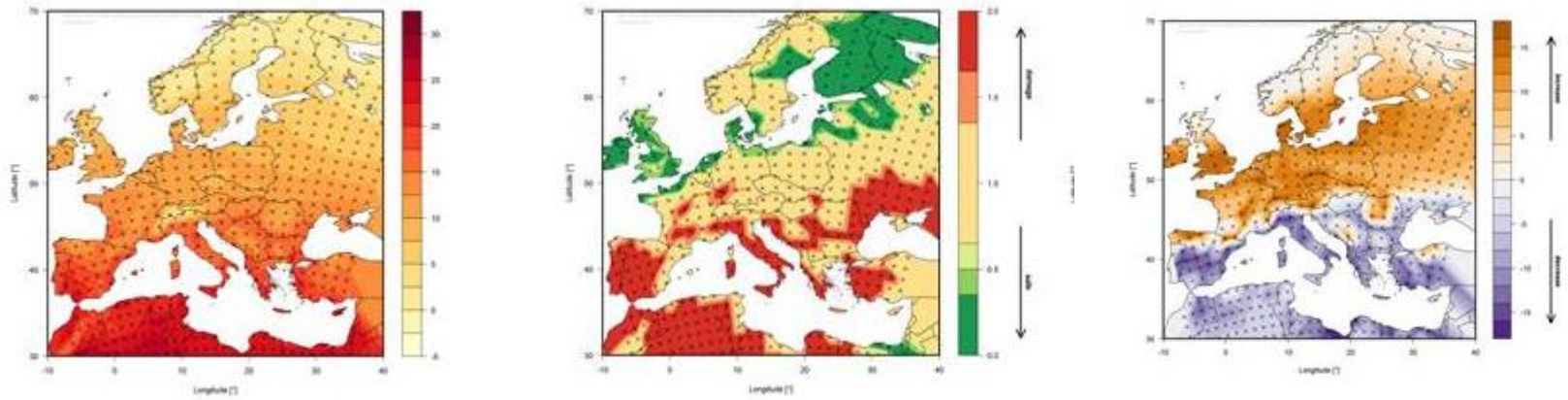


Assessment Methods



under grant agreement No. 226973

Risk assessment for the whole of Europe



Single parameter **Risk category** **Changes**

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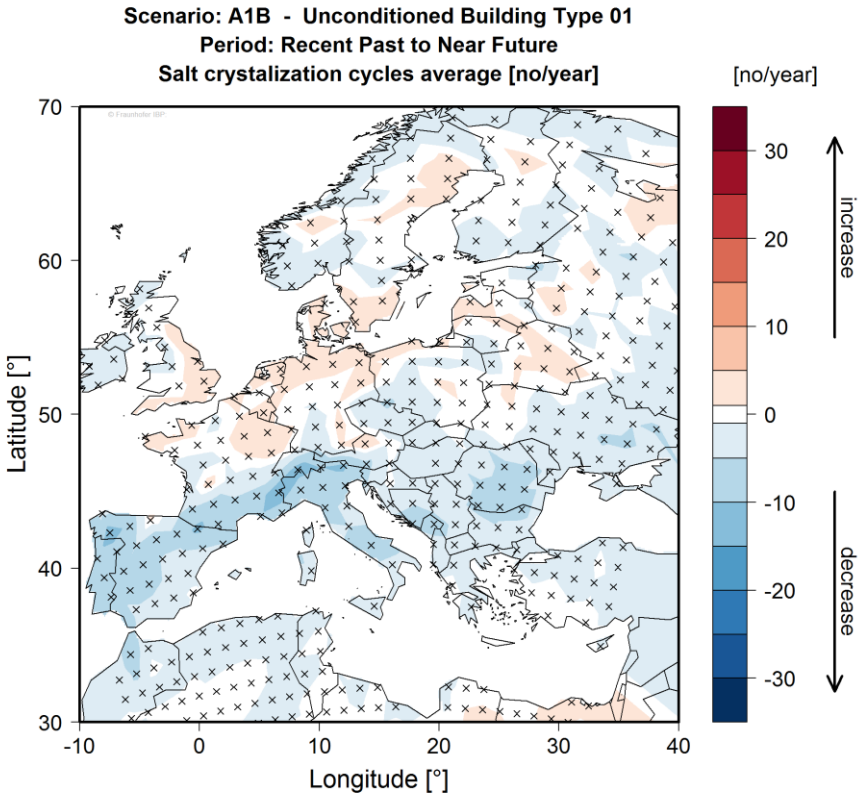
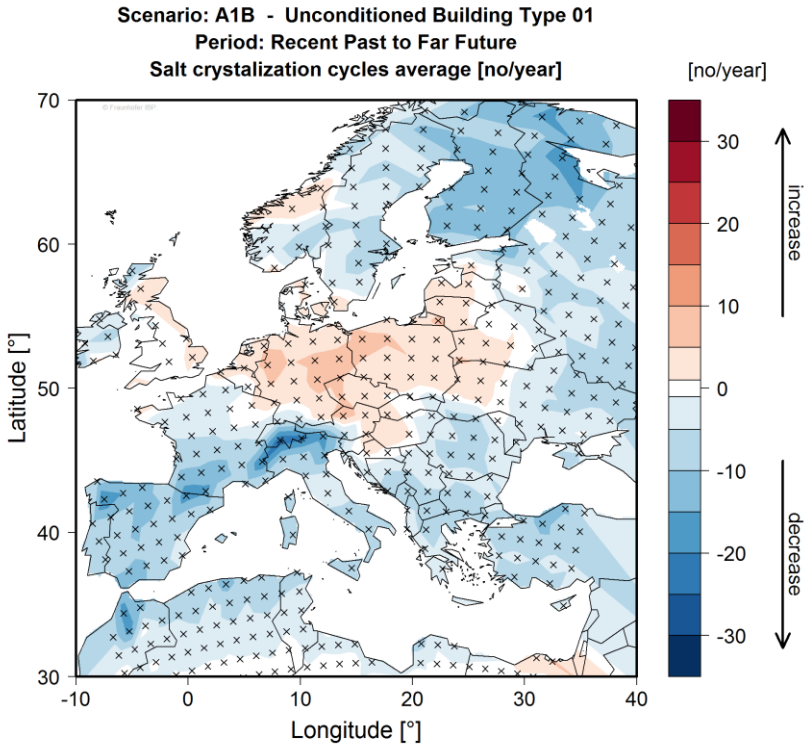
Climate change effects on salt crystallisation cycles





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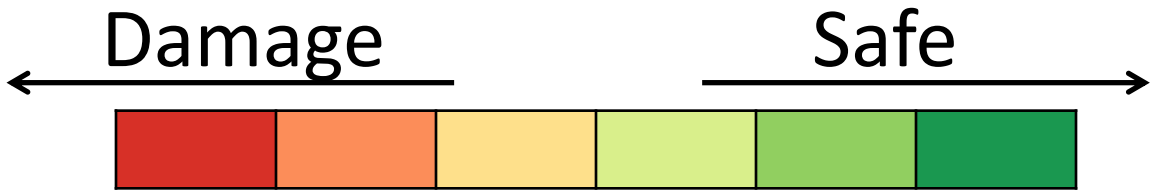
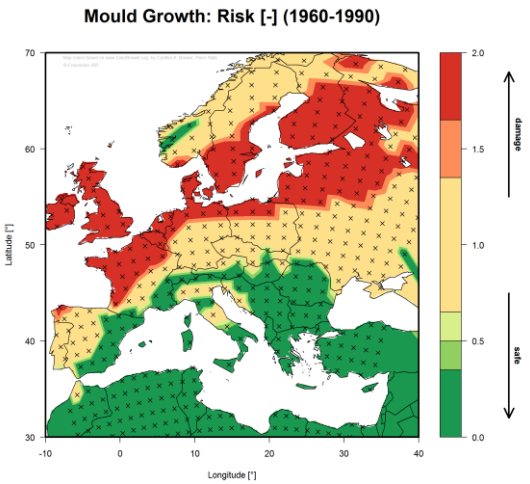
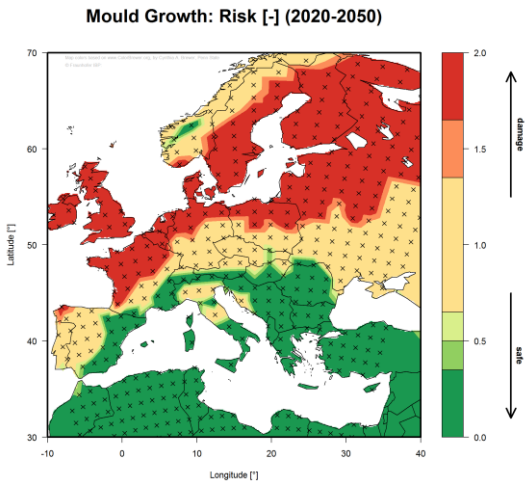
Mapplots: Mould Growth Risk



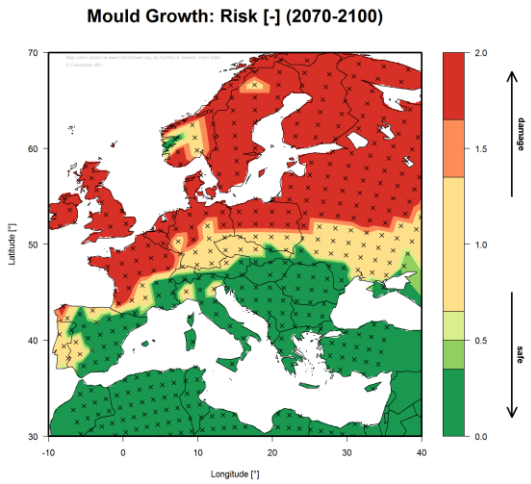
1960 – 1990



2020 – 2050



2070 – 2100



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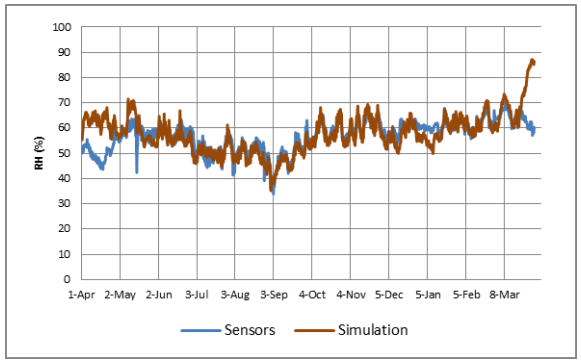
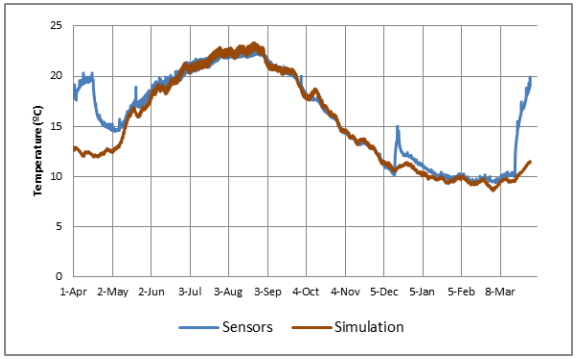
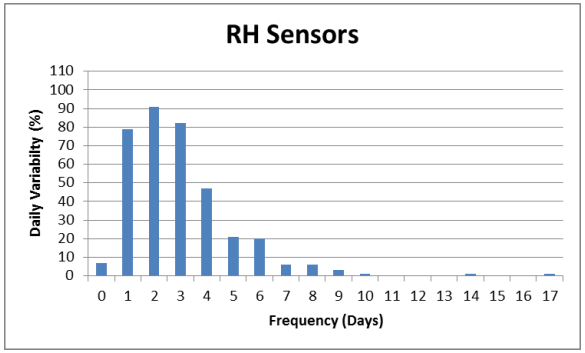
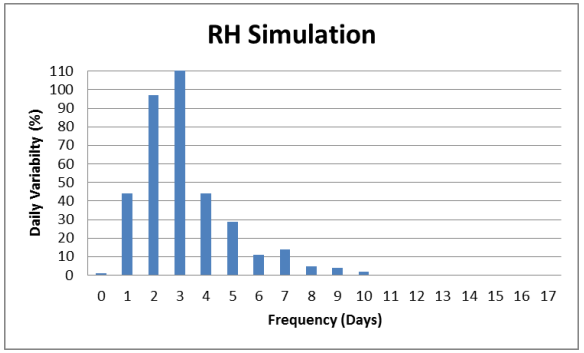
Indoor rH and indoor temperature after 4th simulation





Daily fluctuation range of RH of the final simulation





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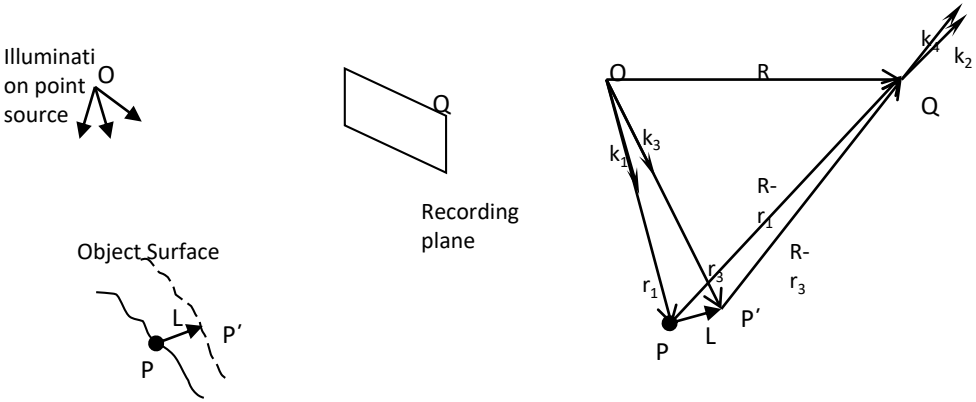
Techniques and sensors

Techniques	Sensors
•**Digital Holographic Speckle Pattern Interferometry** • Mechanical stress in terms of Measurement of surface alterations as a response to environmental fluctuations Structural defect detection, damage generation and propagation	**Glass Sensors** •Environmental corrosivity. •Reaction to temperature, humidity, microorganisms and air pollutants. •Quantification of corrosion rate as D-E by FT-IR.
3D Microscopy Salt crystallization. – •Surface topography •Surface profile – •3D imaging	**Free Water Sensors** • RH threshold levels - Information on wall dampness •Radiellos: Reaction to environmental pollution
•DHSPI/3DM Crack studies	•**KG data loggers**: Data loggers for continuous recording of Relative Humidity and Temperature.

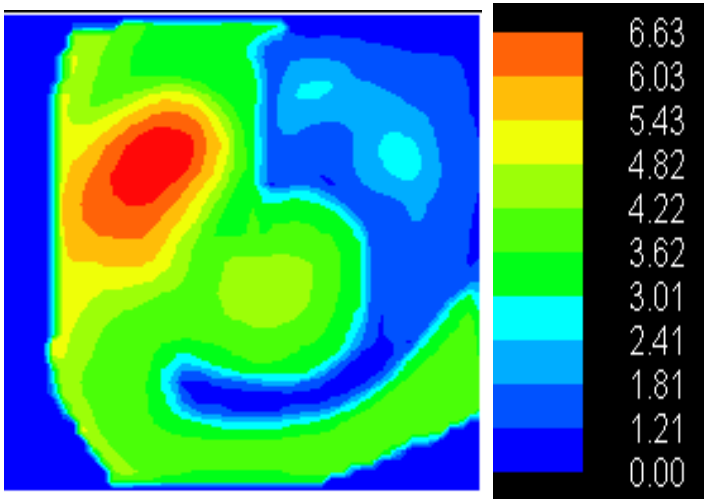
under grant agreement No. 226975

DHSPI Principle

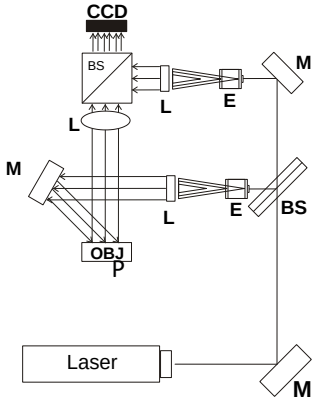


Speckle Interferometry basic principle:
M, mirror; BS, beam splitter; E, expander; L, lens;
OBJ, object

DHSPI Defect detection



Set-up Geometry

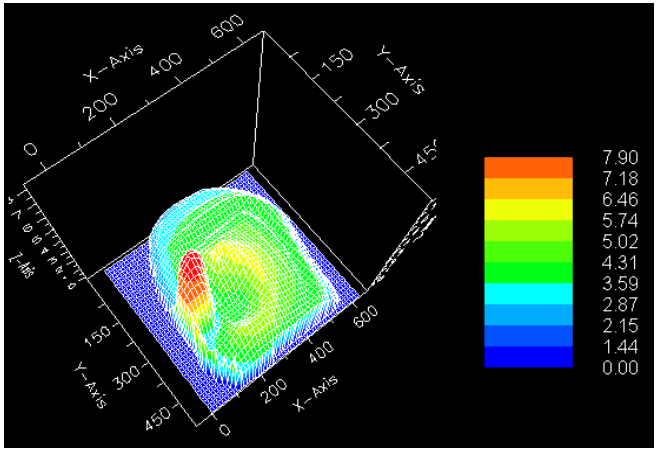


Vector Geometry

$$\delta=(k_2 - k_1)\cdot L \quad \textit{qualitative}$$

$$\begin{bmatrix} K_{1x} & K_{1y} & K_{1z} \\ K_{2x} & K_{2y} & K_{2z} \\ K_{3x} & K_{3y} & K_{3z} \end{bmatrix} \begin{bmatrix} L_x \\ L_y \\ L_z \end{bmatrix} = 2\pi \begin{bmatrix} N_1 \\ N_2 \\ N_3 \end{bmatrix}$$

$$\delta_1=2\pi N_1 \qquad \text{quantitative}$$



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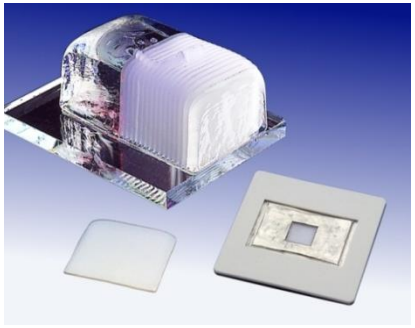
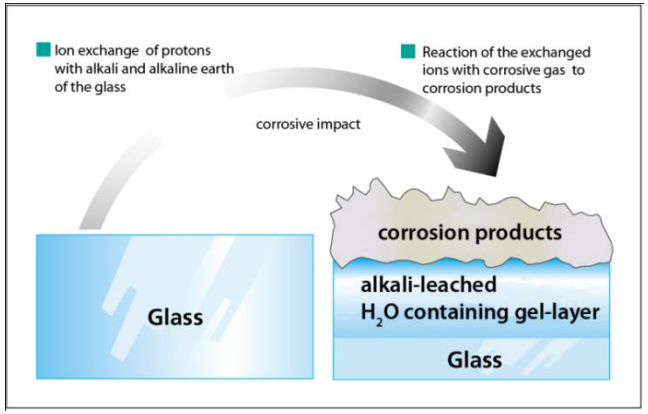
Glass sensors



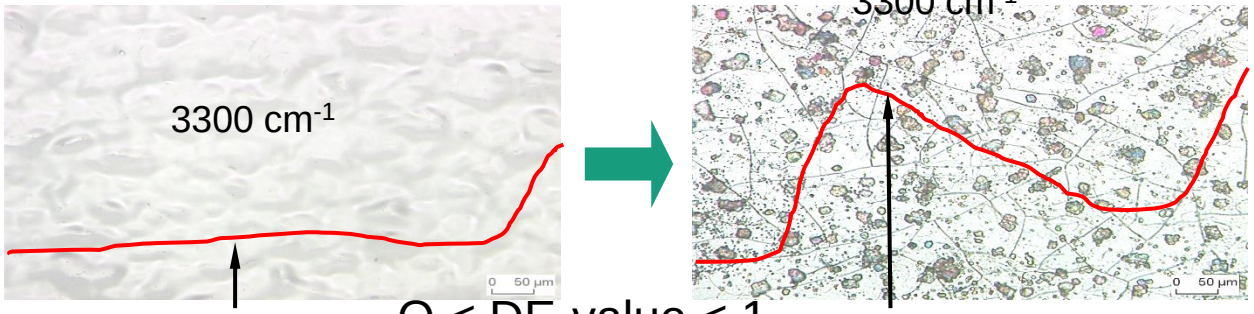
Glass block, partially cut, glass slice, glass sensor.



Effect of the corrosive environment on the glass sensors.

- **Leaching of potassium and calcium ions;**
- **formation of a gel layer**
- **formation of a corrosion crust.**

- Evaluation of the glass sensor by measuring the H_2O /OH-absorption band with FTIR, before and after exposure.



O < DE-value < 1

IR measurement (transmission mode) of H_2O /OH-band before exposure.

corrosion crystals; gel layer formation; cracks after exposure.

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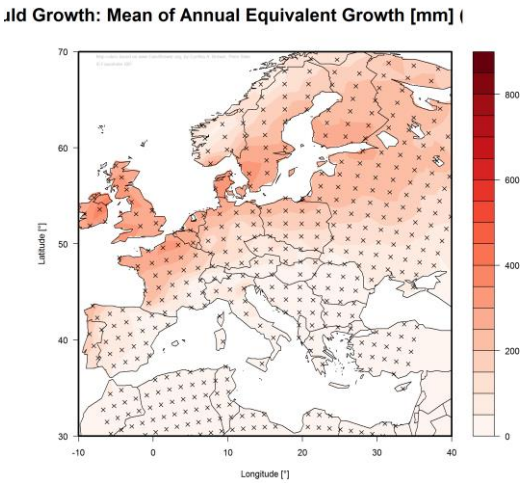
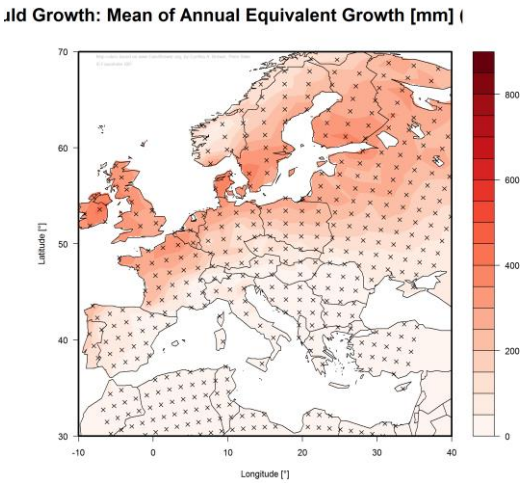
Mean equivalent of Mould Growth [mm/Year]

Increase

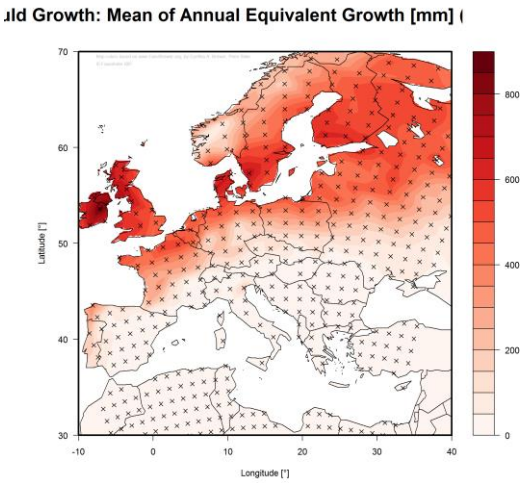
1960 – 1990



2020 – 2050



2070 – 2100



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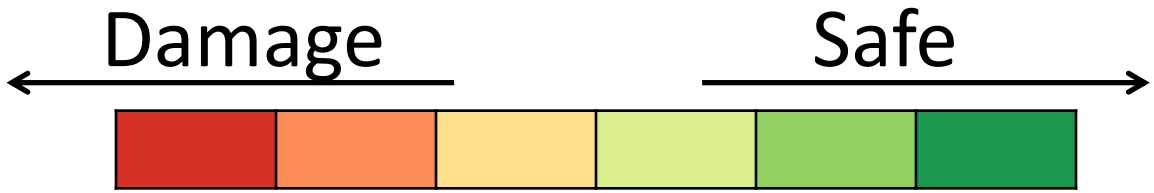
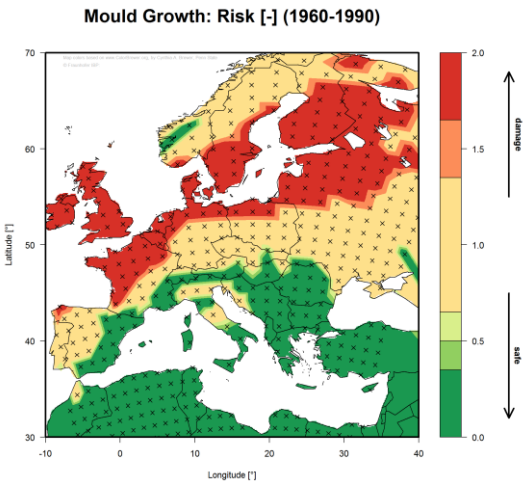
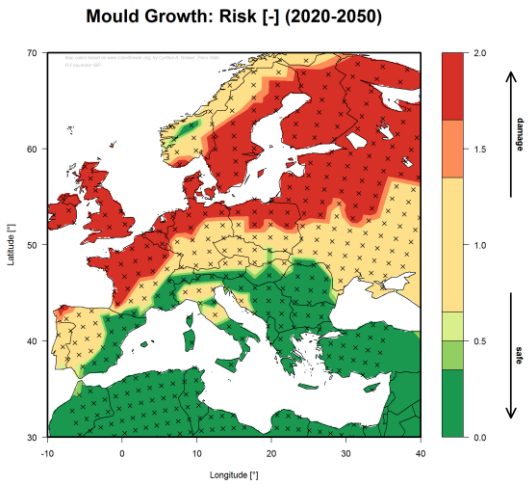
Mapplots: Mould Growth Risk



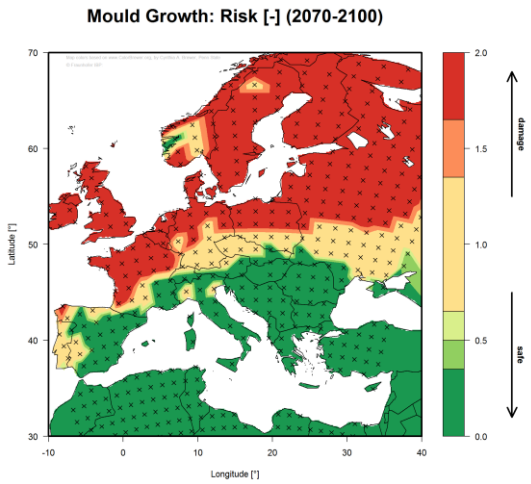
1960 – 1990



2020 – 2050



2070 – 2100



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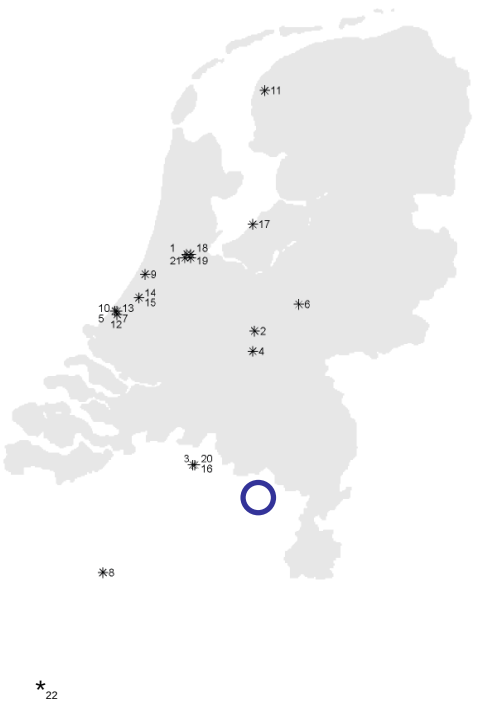
Case study: Castle of Amerongen (Nederlands)

Technische Universiteit Eindhoven University of Technology



1 Museum Our Lord in the Attic
2005/01/24 - 2006/01/23

2 Castle of Amerongen
2003/10/10 - 2005/12/04 and 2008/02/08 - 2010/02/08

3 Begijnhof Museum
2008/03/15 - 2009/09/15

4 Flipje Museum
2008/01/09 - 2009/01/23

5 Museum The Prison Gate
2003/10/27 - 2005/11/03

6 St Hubert Hunting Lodge
2005/12/13 - 2006/12/01

7 Historical Museum of The Hague
2007/07/03 - 2010/01/01

8 Castle Gaasbeek
2007/11/26 - 2009/03/27

9 Castle Keukenhof
2007/11/05 - 2009/12/08

10 Museum Mesdag
2007/04/16 - 2008/04/18

11 Martena Museum
2008/04/23 - 2009/02/01

12 Mauritshuis
2004/10/20 - 2010/12/31

13 Museum Meermanno
2007/04/23 - 2008/02/14

14 National Museum of Antiquities
2006/12/07 - 2007/12/10

15 Depot Raamsteeg
2008/10/31 - 2009/12/08

16 Nationaal Museum van de Speelkaart
2008/03/15 - 2009/09/15

17 National repository for ship archaeology
2007/12/18 - 2010/01/01

18 Netherlands Maritime Museum Amsterdam
2003/12/23 - 2009/12/31

19 Tropenmuseum
2006/12/19 - 2009/03/12

20 Taxandria Museum
2008/03/15 - 2009/09/15

21 Van Gogh Museum
2007/07/31 - 2009/01/01

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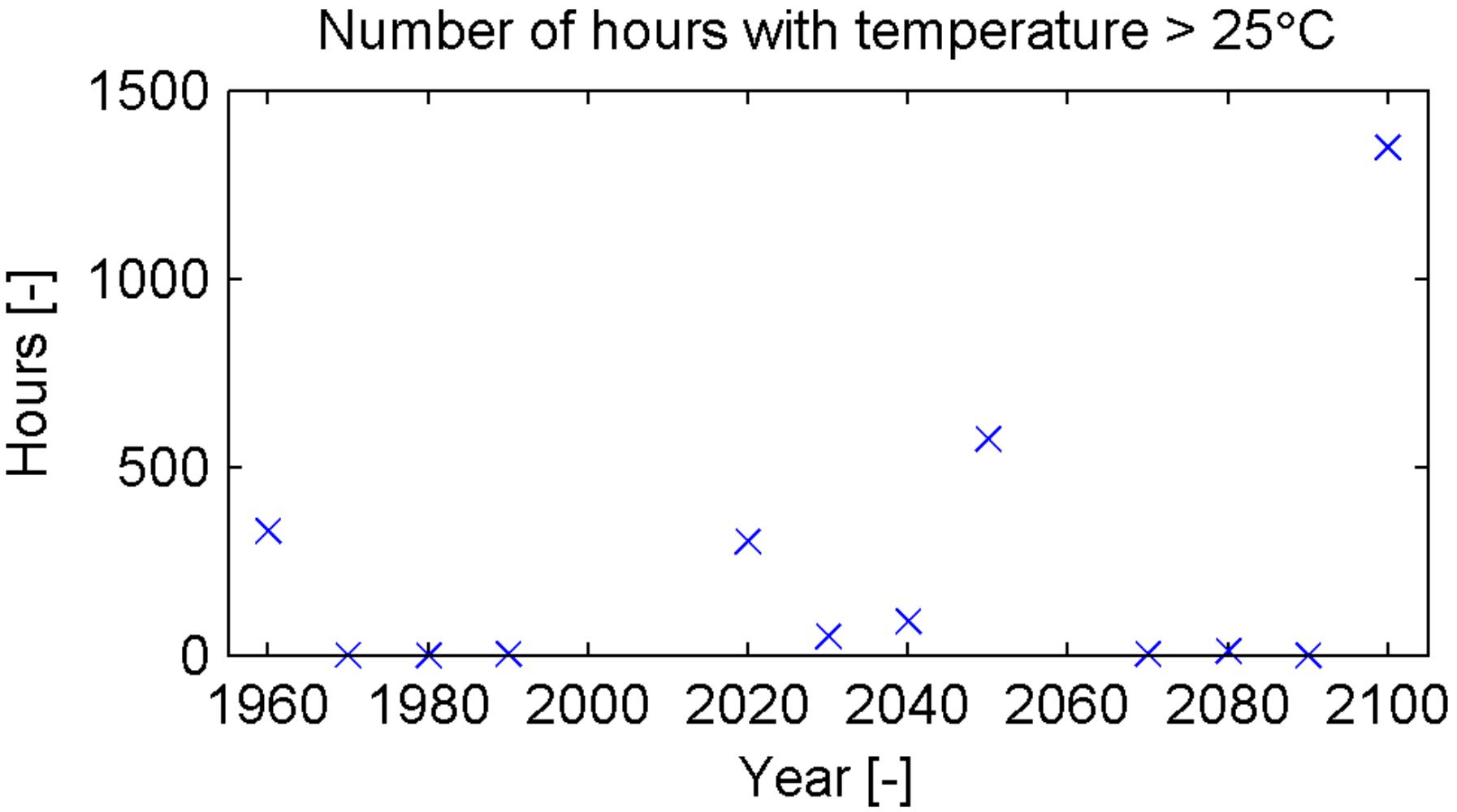

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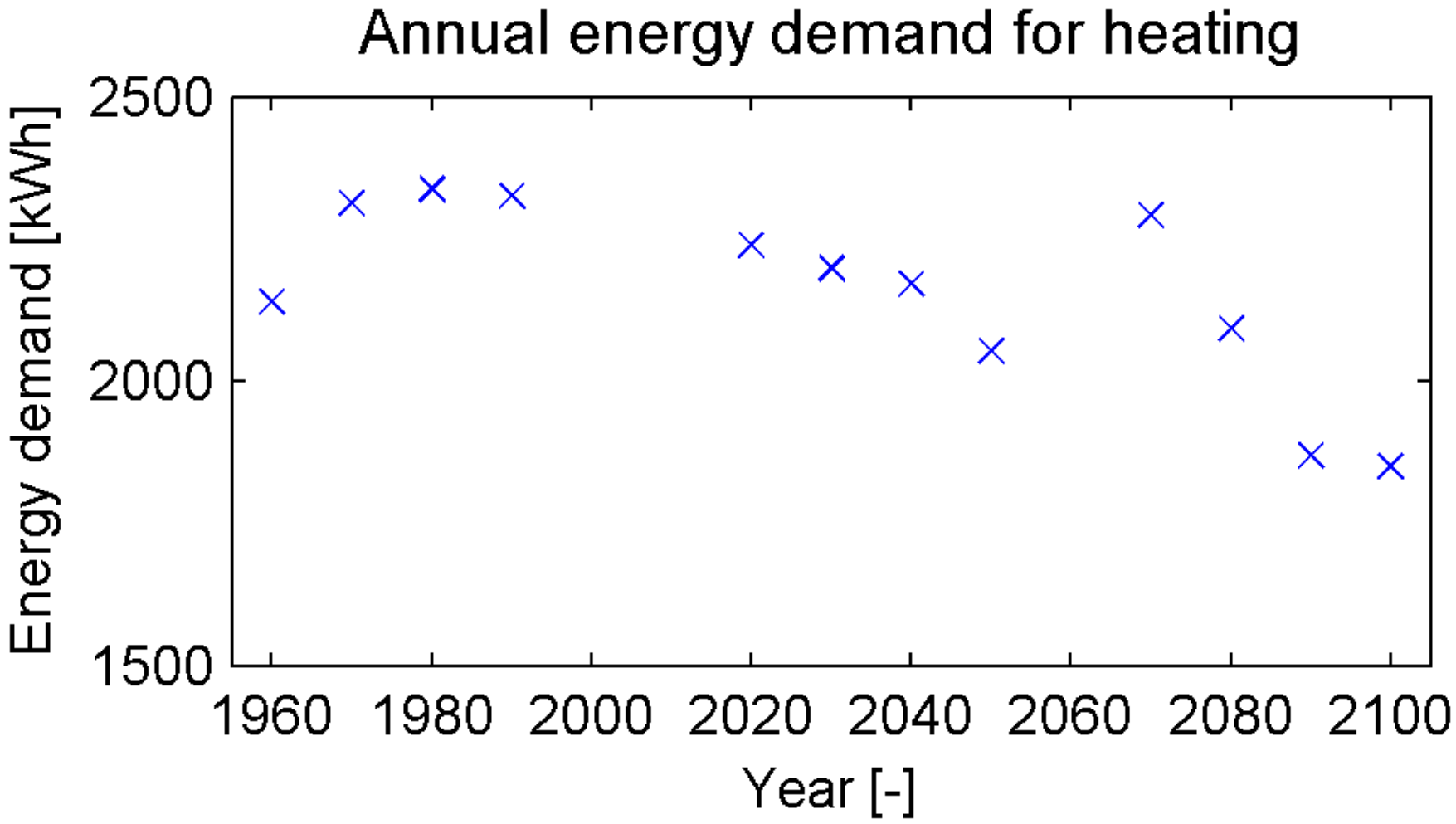

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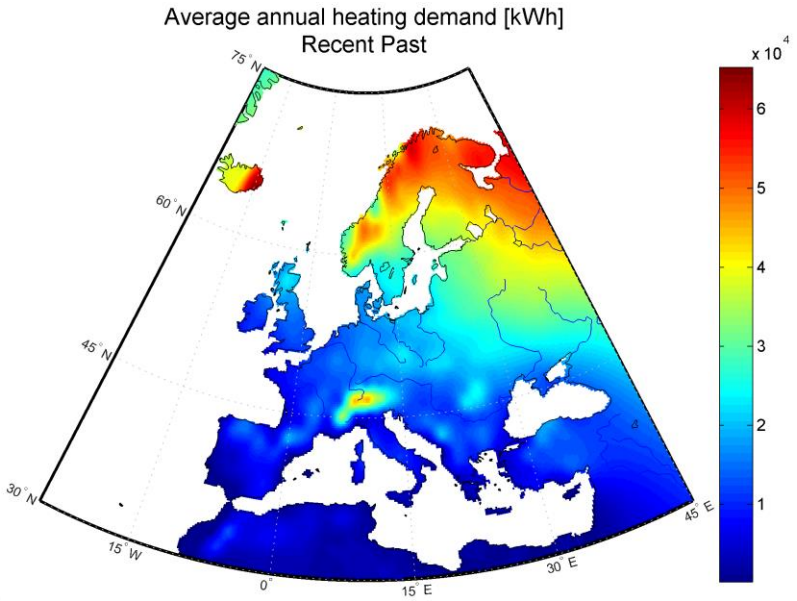
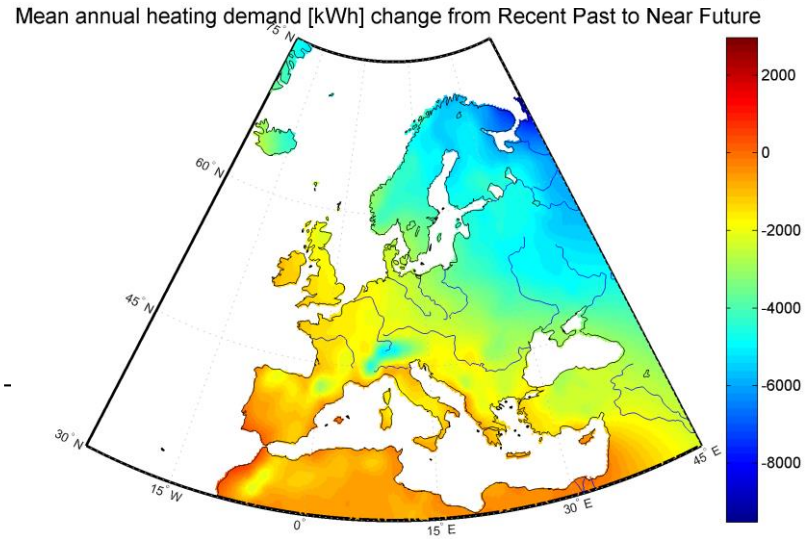
Mean annual energy demand change for heating



TU/e Technische Universiteit Eindhoven University of Technology



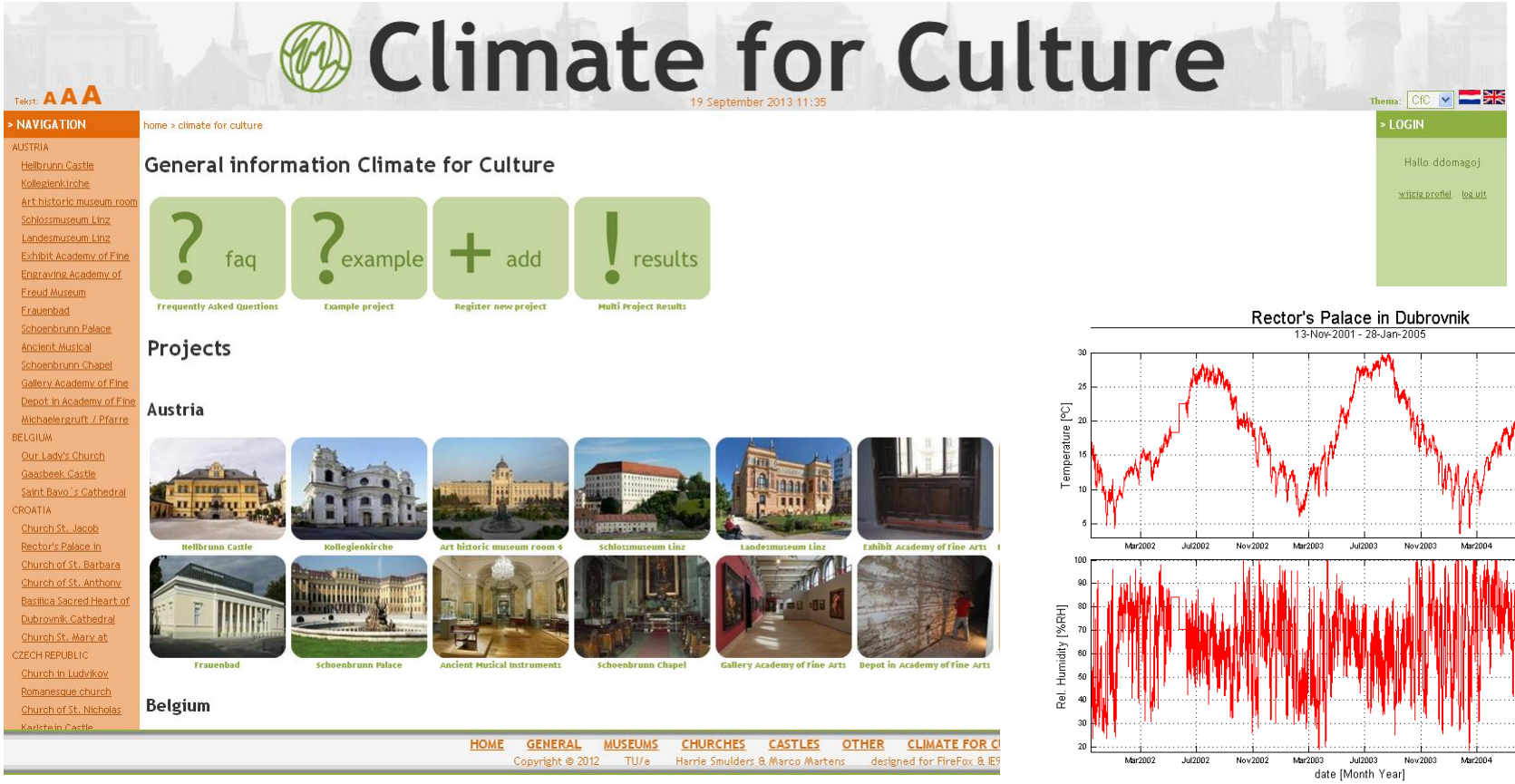
Climate

Climate for Culture

Datenbank

TU/e Technische Universiteit Eindhoven University of Technology

Kybertec



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Detailed comparison of measurements 2012 and simulation

Temperature

Parameter	Simulation T [°C]	Measurement T [°C]	Delta [K]	Assessment
Range	28,9	29,2	0,3	excellent
1% / 99% Quantil	26,3	25,4	0,9	excellent
Maximum	21,9	23,9	2,0	acceptable
99% Quantil	20,9	21,1	0,2	excellent
Median	11,0	11,4	0,4	excellent
1% Quantil	-5,4	-4,3	1,1	acceptable
Minimum	-7,0	-5,4	1,6	acceptable
Mean	10,1	10,5	0,4	excellent
Correlation Coefficient			0,994	excellent

Relative Humidity

Parameter	Simulation RH [%]	Measurement RH [%]	Delta RH [%]	Assessment
Range	48,1	52,1	4,0	excellent
1% / 99% Quantil	34,1	33,7	0,4	excellent
Maximum	100	96,6	3,4	excellent
99% Quantil	92,8	91,9	0,9	excellent
Median	76,3	78,7	2,4	excellent
1% Quantil	58,8	58,2	0,6	excellent
Minimum	51,9	44,6	7,3	acceptable
Mean	76,0	77,8	1,8	excellent
Correlation Coefficient			0,912	acceptable

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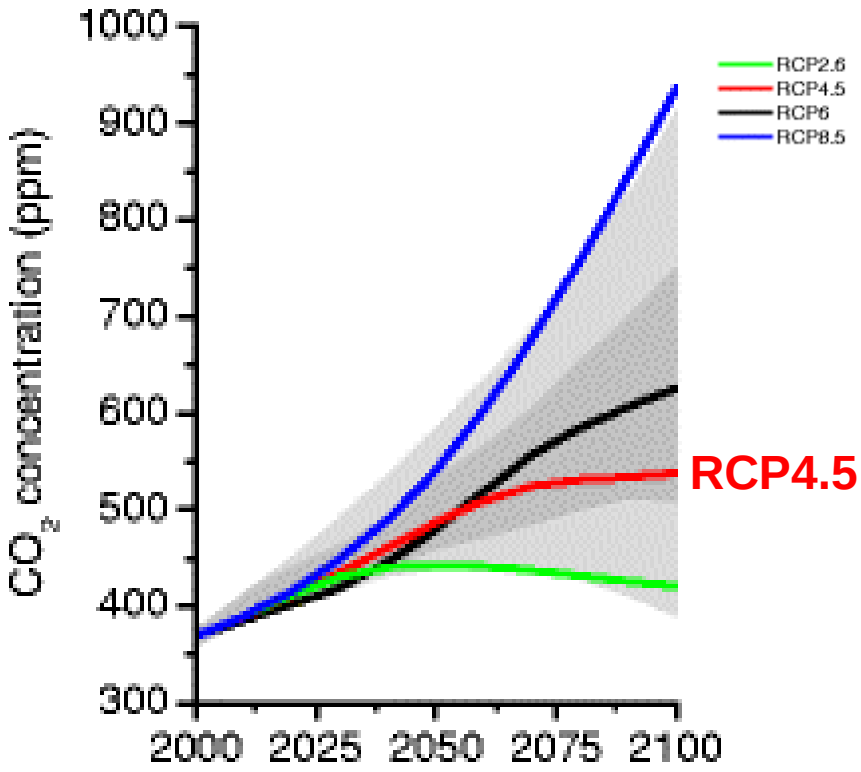
Climate modelling - two moderate IPCC emission scenarios RCP4.5

Representative Concentration Pathway (RCP) 4.5 is a scenario describing the long-term, global emissions of greenhouse gases and short-lived species. Further, it takes into account land-use-land-cover which stabilizes radiative forcing at 4.5 W/m² (approximately 650 ppm CO2-equivalent) in the year 2100 without ever exceeding that value [Allison et al.]

CO_2 concentrations



Source: http://www.dkrz.de/

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"If a man will begin with certainties he shall end in doubts,

- but if he will be content to begin with doubts he shall end in certainties"

Francis Bacon (1561 - 1626)

English philosopher, statesman, scientist, jurist and author

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Climate for Culture

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