The Water Cycle in a Changing Climate: High-Resolution Simulations

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ETH zürich

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Hydrological Impacts of Extreme Precipitation

Flash floods

Saanen (Switzerland), Jul 2010

Landslides

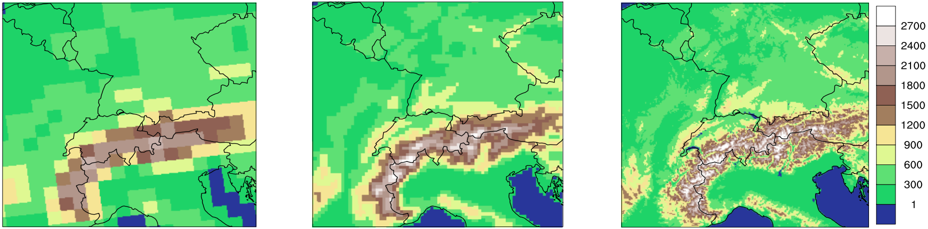
Graubünden (Switzerland), Aug 2014

Snow Avalanches

Galtür (Austria), Feb 1999

Numerical modeling of climate

Global climate model 50 km | Regional climate model 12 km | Convection-resolving model 2 km



- RCM are used in CORDEX (Coordinated Regional Downscaling Experiment) at 0.11° and 0.44° horizontal resolution (12 and 50km)
  -see e.g.: Giorgi et al., 2006; Jones et al., 2011; Jacob et al., 2013; Kotlarski et al., 2014; Giorgi et al., 2016; Kotlarski et al., In prep.
- CRM: Convection-resolving model enables explicit simulation of convection (e.g., thunderstorms, rain showers)
  -see e.g.: Grell et al., 2000; Hohenegger et al., 2008; Knote et al., 2010; Kendon et al., 2012, 2014, 2016; Rasmussen et al., 2011, 2014; Ban et al., 2014, 2015; Prein et al., 2015, Leutwyler et al., 2016

Outline

EURO-CORDEX: Analysis of Snow Cover

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Convection-Resolving Climate Simulations: Evaluation & Climate Change Projections

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EURO-CORDEX: Analysis of Snow Cover

**Convection-Resolving Climate Simulations:
Evaluation & Climate Change Projections**

European-Scale Convection-Resolving Climate Simulations (crCLIM)

EURO-CORDEX

Analysis of Snow Cover

EURO-CORDEX Snow Cover Evaluation

Mean Annual Cycle of Total Snow Covered Area in Europe

ERA-Interim driven EUR-11 simulations versus NSIDC satellite data (1989-2008)

- Mean snow-covered area is mostly underestimated

(Kotlarski et al., In preparation)

EURO-CORDEX Snow Cover Evaluation

Bias in Number of Snow-Covered Days per year

ERA-Interim driven EUR-11 simulations versus NSIDC satellite data (1989-2008)

- Underestimation of number of snow days by most experiments over most parts of Europe

(Kotlarski et al., In preparation)

EURO-CORDEX Snow Cover Projections

Change in the Mean November-April Snow Water Equivalent

GCM driven EUR-11 simulations, RCP8.5 (1971-2000 to 2071-2100)

- Large decrease in mean snow water equivalent in all areas

(Kotlarski et al., In preparation)

EURO-CORDEX Snowfall Projections Alps

Change in the Mean September-May Snowfall

GCM driven EUR-11 simulations, RCP8.5 (1971-2000 to 2071-2100)

(Frei et al., In preparation)

EURO-CORDEX Temperature Projections Alps

Change in Mean MAM and JJA 2m Temperature (vertical profile)
GCM driven EUR-11 simulations, RCP4.5 & RCP8.5 (1981-2010 to 2070-2099)

- Amplification of warming by decreasing snow cover (snow-albedo feedback)

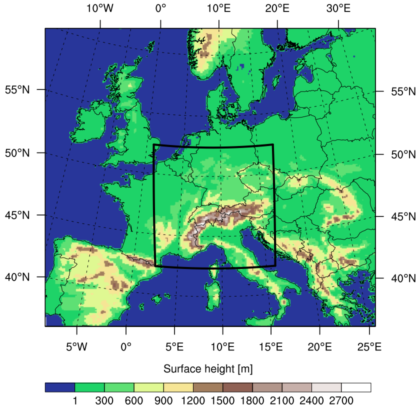
(Kotlarski et al., In preparation)

Convection-Resolving Climate Simulations

Setup

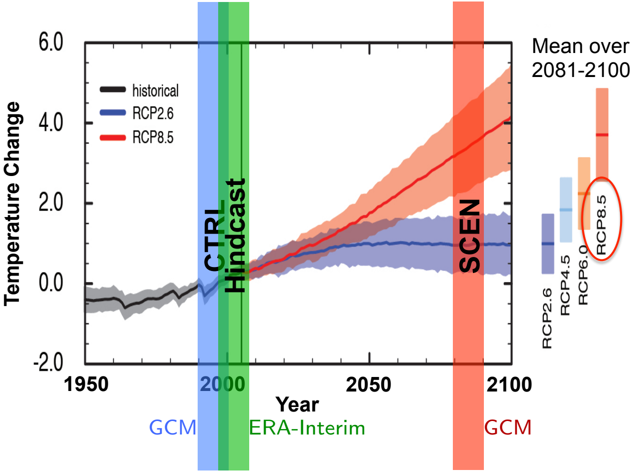
Two-step one-way nesting: BC ⇒ CPM12 ⇒ CRM2

- CPM12 and CRM2 use COSMO-CLM v4.14
- Boundary Conditions: ERA-Interim reanalysis & MPI-ESM-LR (RCP8.5)
- CPM12: Convection–Parameterizing Model
  - $\triangle$x,y=12 km (0.11°)
  - XxYxZ=260x228x60
  - Parametrization of convection: Tiedtke
- CRM2: Convection–Resolving Model
  - $\triangle$x,y=2.2 km (0.02°)
  - XxYxZ=500x500x60
  - Deep convection explicitly resolved
  - Shallow convection: Tiedtke



- The setup is similar to MeteoSwiss for NWP
- The numerical simulations have been performed on the CRAY XT5 and CRAY XE6 at the Swiss National Supercomputing Center (CSCS)

Experiments: CRM Simulations for the Greater Alpine Region



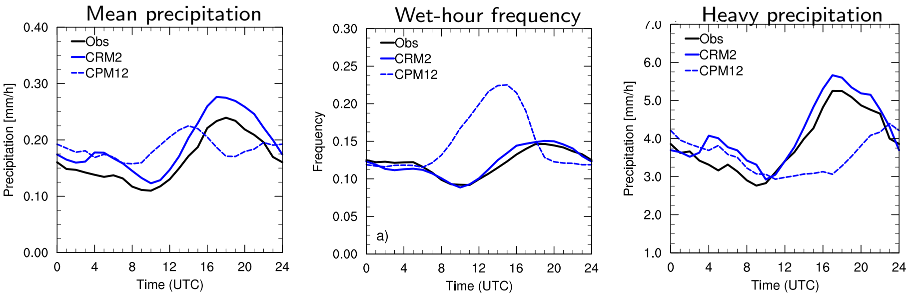
- Wallclock time: 1×10y CRM2 → ≈4-8months

[IPCC AR5]

Convection-Resolving Climate Simulations: Evaluation

- ERA-Interim driven simulations (1998–2007)

Diurnal Cycle of Summer Precipitation



[Analysis for 62 Swiss stations]

- CRM2 realistically simulates amplitude and phase of the diurnal cycle

(Ban et al., 2015 GRL)

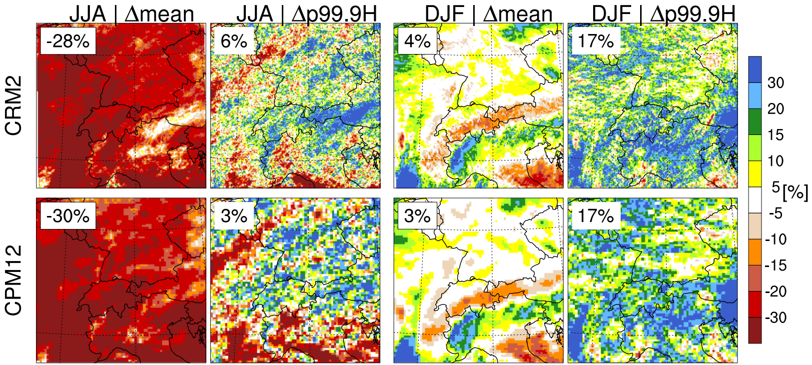
Evaluation of Precipitation – Average across 62 Swiss Stations

→ CRM2 improves the simulation of precipitation in the winter (DJF) and summer (JJA) season

Convection-Resolving Climate Simulations: Climate Change Projections

- based on GCM-driven scenarios for 2081-2090 (RCP8.5) versus 1991-2000

Projections of Mean and Heavy Precipitation



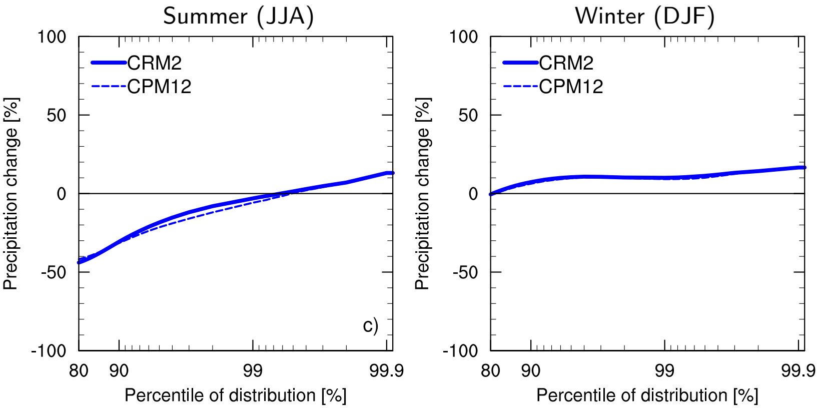
Summer (JJA):

- Increase in heavy precipitation despite an overall drying
- Decrease in large-scale, and increase in convective precipitation (Giorgi et al., 2016, Nature Geoscience)

Winter (DJF):

- CRM2 and CPM12 show similar changes

Relative Changes of Precipitation on Daily Timescales

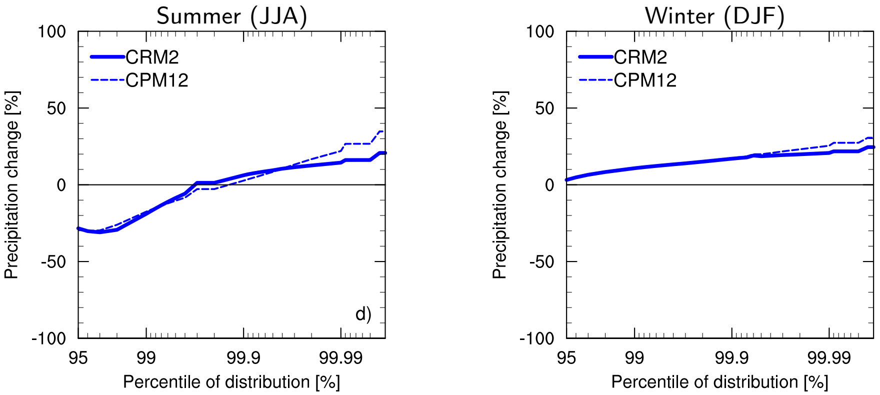


[Average across the CRM2 domain]

- Close agreement of CRM2 and CPM12

(Ban et al., 2015 GRL)

Relative Changes of Precipitation on Hourly Timescales



[Average across the CRM2 domain]

- CRM2 exhibits smaller changes than CPM12

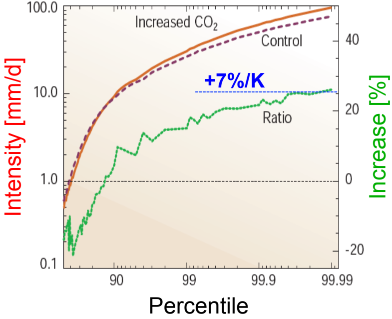
(Ban et al., 2015 GRL)

Link Between Temperature Change and Extreme Precipitation Change

Moistening of the atmosphere is determined by Clausius-Clapeyron relation:

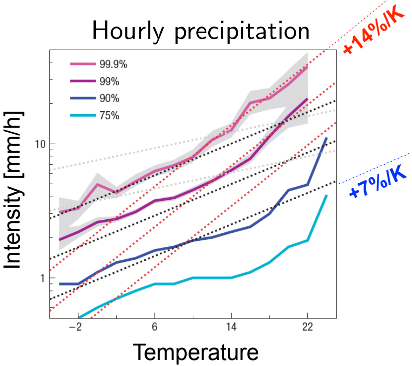
$$\frac{1}{e_{sat}}\frac{de_{sat}}{dT} \approx 6 - 7\%/K \quad \Longrightarrow \quad \frac{1}{P_{extreme}}\frac{dP_{extreme}}{dT} \approx 6 - 7\%/K$$

Daily precipitation



[Allen and Ingram, 2002]

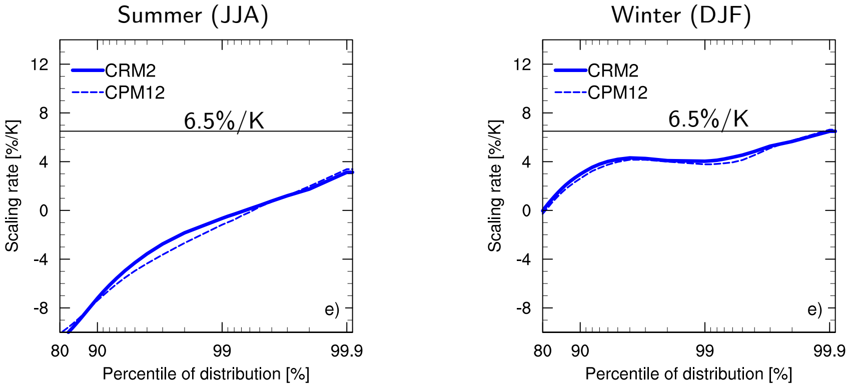
Hourly precipitation



[Lenderink and van Meijgaard, 2008]

- Do heavy hourly precipitation events increase at adiabatic (∼6-7 %/K) or super-adiabatic (∼14 %/K) rate?

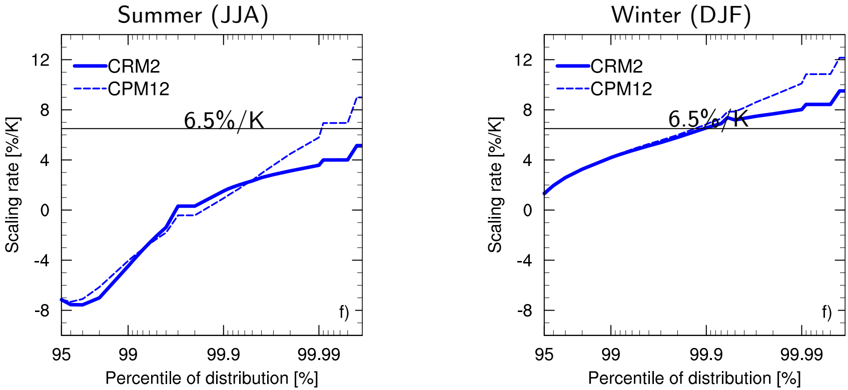
Link Between Temperature Change and Extreme Daily Precipitation Change



⇒ Extreme daily precipitation asymptotically intensify with the Clausius-Clapeyron relation

(Ban et al., 2015)

Link Between Temperature Change and Extreme Hourly Precipitation Change



⇒ Summer (JJA): Extreme hourly precipitation asymptotically intensify with the Clausius-Clapeyron relation

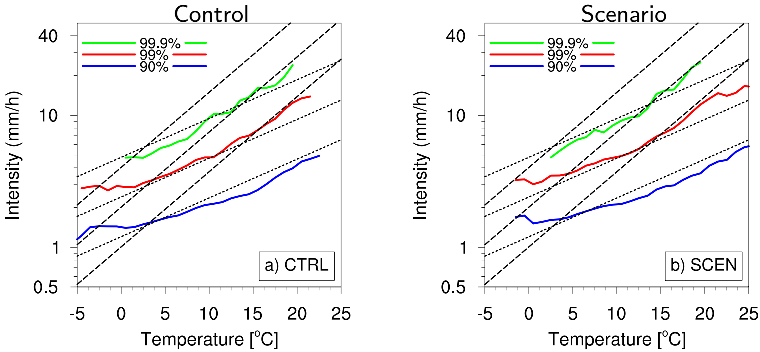
⇒ Winter (DJF): Changes in extreme hourly precipitation exceeds the Clausius-Clapeyron rate

Although...

(Ban et al., 2015)

Link Between Temperature Change and Extreme Hourly Precipitation Change

Scaling of Extreme Hourly Precipitation Events



...CRM2 exhibits super-adiabatic scaling for extreme warm-season precipitation, and adiabatic for cold-season precipitation in both Control and Scenario simulations

⇒ Indicates that scaling of extreme precipitation with temperature in present-day climate can not be extrapolated into the future

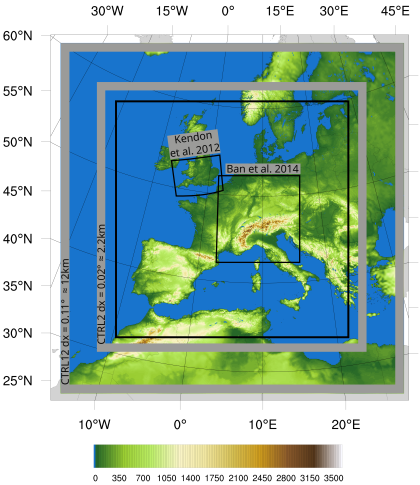
(Ban et al., 2015)

European-Scale Convection-Resolving Climate Simulations (crCLIM)

http://www.c2sm.ethz.ch/research/crCLIM.html

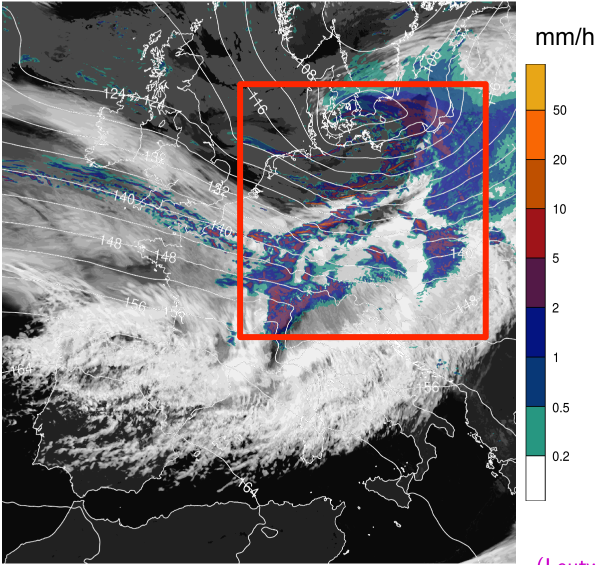
European-Scale Convection-Resolving Climate Simulations (crCLIM)

- Two-step one-way nesting: ERA-Interim ⇒ 12km ⇒ 2.2km
- X×Y×Z=1536×1536×60 grid points
- GPU version of COSMO (Fuhrer et al., 2014)
  - Dynamical core rewritten in C++
  - Parameterizations use OpenACC
  - Runs on Piz Daint (Cray XC30, CSCS)
  - Used for operational NWP at MeteoSwiss (Δx=1 km)
- Wall-clock time: 1 year ⇒ 5 days
- 1st 10-year long simulation: 1999-2008 ⇒ Completed



(Leutwyler et al., 2016)

Winter Storm Kyrill

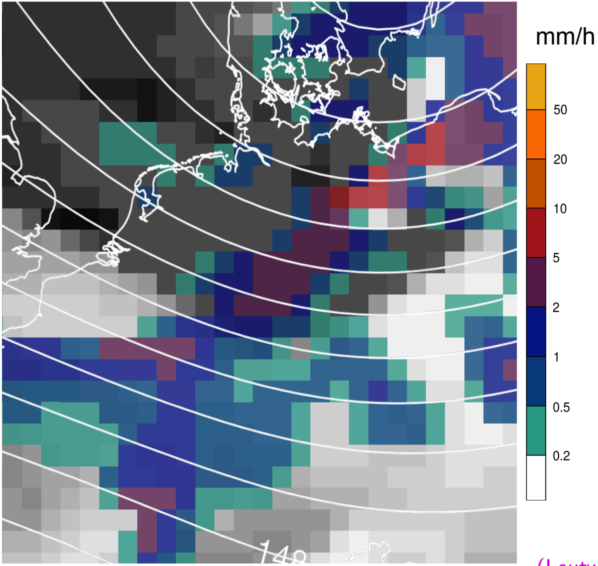


Jan 18, 2007, 18 UTC

$\Delta x = 2$ km

(Leutwyler et al., 2016 GMD)

Winter Storm Kyrill

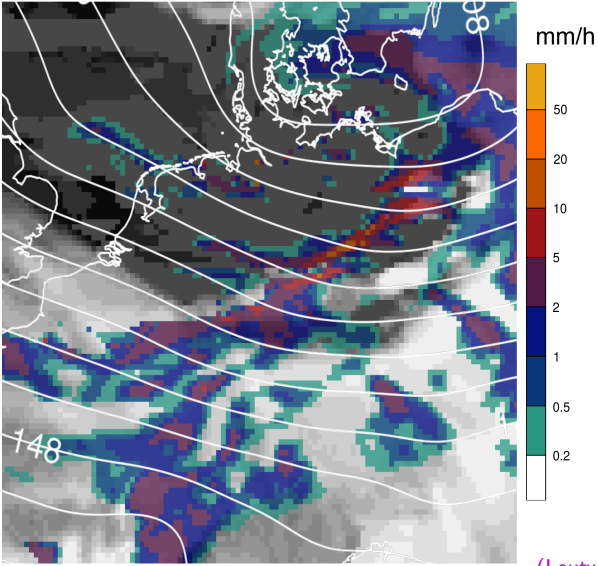


Jan 18, 2007, 18 UTC

$\Delta x = 50\,\mathrm{km}$

(Leutwyler et al., 2016 GMD)

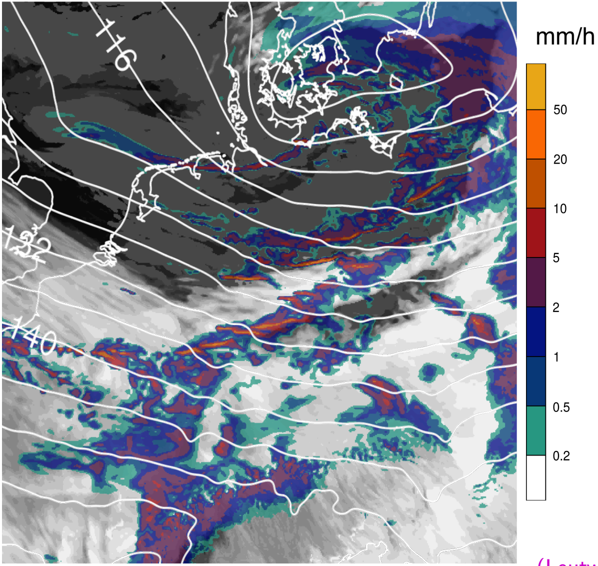
Winter Storm Kyrill



Jan 18, 2007, 18 UTC
$\Delta x = 12\,\text{km}$

(Leutwyler et al., 2016 GMD)

Winter Storm Kyrill



Jan 18, 2007, 18 UTC

$\Delta x = 2\,km$

(Leutwyler et al., 2016 GMD)

Summary

EURO-CORDEX

- Most experiments underestimate the snow cover
- Decrease of snow cover amplifies the warming at higher elevations (snow-albedo feedback)

Convection-Resolving Climate Simulations

- CRM2 improves the simulation of precipitation in all seasons and on all time scales (especially on the sub-daily)
- Close agreement of CRM2 and CPM12 regarding the changes in daily precipitation; for hourly extremes CRM2 exhibits smaller changes than CPM12
- Changes in extreme JJA precipitation qualitatively scale with the Clausius-Clapeyron rate. In DJF the change exceeds the Clausius-Clapeyron rate for short-term extreme precipitation.

European-Scale Convection-Resolving Climate Simulations (crCLIM)

- COSMO-GPU prototype enables climate simulations on large computational domains with a reasonable time-to-solution, and has a great potential for future climate studies

Thank you for your attention!