Creating weather data for climate change impact studies
(focus on weather generators and climate change scenarios)

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www.ufa.cas.cz/dub/crop/crop.htm

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About my lecture

• The main topic: creating weather series for impact models (crop models & other models) which represent present and future climates

• Parts of the lecture (... will also depend on the time):
  1. introduction (our research group, methodology, ...)
  2. weather generators
  3. climate change scenarios (linkable with WG!) .......

• This presentation is mostly based on
  – papers and conference contributions of our research group (MZLU + me)
  – my lectures in Sardinia (Sassari Univ., Alghero summer school), 2009

• web resources:
  – papers + conf. contributions of our group: www.ufa.cas.cz/dub/crop/crop.htm
  – this lecture will be also made available on our web
Introduction

1. our research group (MZLU + me)

- Mendel University of Agriculture and Forestry:
  - crop modelling (CERES-Wheat/Maize/Barley, WOFOST, STICS)
  - pest & diseases modelling (ECAMON, Climex, Dymex)
  - soil modelling (SoilClim)
  - modelling for agroclimatological indices (AgriClim), ....
  - model for snow cover: SnowMAUSE
  - phenology: observations & modelling (FenClim)

Demands on climate & weather data to run their models under present + changed climate.

my role in our team:
- construction of climate change scenarios (from GCM & RCM)
- construction of input weather series representing “now” and “future” (using the weather generator)
- linking the scenarios & WG with MZLU’s models
1.1.1 Crops

- **crop modelling** (= our first topic – since 1995 /CERES/)
  - CERES
  - WOFOST, STICS

- **crop yield forecasting:**
  - PERUN (based on WOFOST + Met&Rol)

- **impacts of climate change**
  - **sensitivity** to changes in structure of input weather
  - **GCM-based scenarios** based on IPCC datasets
  - **spatial assessments**
    - crop modelling + interpolation
    - or: interpolation of WG + simulation
  - **adaptation** through
    - different cultivars
    - shifting the sowing date
    - Increasing soil water reserves

- **references** ([www.ufa.cas.cz/dub/crop/crop.htm](http://www.ufa.cas.cz/dub/crop/crop.htm))
  - Dubrovsky et al., 2000
  - Zalud and Dubrovsky, 2002
  - Trnka et al. 2004a, 2004b
  + conference contributions

1.1.2 Pests and diseases

- **observations:**
  - MZLU's observations (1961-2008); for some pests (diseases) archives reach back to late 19th century

- **trends and climate change impacts on**
  - Colorado potato beetle /……. figure:
  - European corn borer

- **modelling:**
  - **Climex**: climate matching software developed by CSIRO (Australia)
  - **Dymex**: modelling tool enabling easy custom-base development of own pest-disease models
  - **ECAMON**: model for estimating suitability of environmental conditions for European Corn Borer populations (developed by Trnka)

- **references:**
  - Trnka et al., 2007, Ecological Modelling 207, 61-84
  - Kocmánková et al., 2008, Plant Protection
  - Kocmankova et al., 2008, EMS
  - Kocmankova et al., 2009, EGU

Ecoclimatic Index [Climex model] of Colorado potato beetle in CZ (1961-90; 1991-2000; 2025; 2050) [Kocmankova et al., 2009, EGU]
Phenology

- **focus on:**
  - trends in phenophases
  - climate change impacts (via FenoClim model now being under development)

- **observations** (South Moravia, 1951-2009):
  - **Trees, shrubs and plants:** in natural reserves and agriculture systems (around 25 species) at 6 locations
  - **Birds:** 4 species (including information on the food chain)

- **references:**
  - Bartosova et al., 2008, EMS
  - Bartosova et al., 2009, EGU

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Drought

- **2003:** collaboration with NDMC in Lincoln-Nebraska started

- **focus on**
  - drought indices (SPI, PDSI, Z) (their use and modification)
  - projection of future drought conditions (CZ, Europe, globe)
  - development of soil model SoilClim (see next slide)
  - impacts on yields [Fig. ←]

- **references:**
  - Trnka et al., 2007, *Plant Soil Environ.*
  + conference contributions

Statistical significance of relation between rZ and crop yields at district level [Hlavinka et al., 2007, EMS; Hlavinka et al., 2009, *Agric. For. Meteorol.*]

Projection of future drought conditions in terms of the relative Z-index [Dubrovsky et al., 2007, AGU]
**Soil modelling**

**SoilClim** = model (by Trnka + collaboration with NDMC) based on Newhall model

**inputs:**
- soil properties affecting water movement and heat transfer
- daily weather series (SRAD, TMAX, TMIN, PREC, VAPO, WIND)

**modelled characteristics:**
- Soil hydric and thermic regimes
- „vegetation window“
- drought and wet events, etc.

**applications:**
- projections of future soil climate in Europe and U.S.

**references:**
- Trnka et al. 2008, AGU
- Hlavinka et al., 2009, EGU

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**1.1.5 Climate change impacts on crops - methodology**

- multi-year simulations are made to assess mean and variability
- other models may be used instead of the crop model
- crop model is assumed to be calibrated and set to deal with variable climate conditions (e.g. “automatic” sowing day is used)
Q: How to get site-specific weather series representing future climate?

- GCM?

+ presently the best available tool (and hopefully ever improving) to simulate future climate

+ numerous GCM simulations of present & future climate are freely available (e.g. IPCC database)

but:

? What is the quality of the GCM output?

? Is GCM output directly applicable?

1.3.1 direct use of GCM output? No!

• low resolution & smoothed relief implies:
  - shores are smoothed → no Sardinia, no Italy!
  - mountains are lowered

• sub-grid phenomena (e.g. convection) are not adequately simulated and must be parameterised

• statistical structure of site-specific surface weather is misrepresented:
  - strong biases
  - different annual cycle
  - different shape of PDFs (e.g. PREC)
  - different persistence (~ day-to-day variability)

• the gap between what....

... we have (large-resolution GCM output)

... we need (site-specific surf.wea.series)

is bridged by downscaling (in space and/or in time)

Europe in AR3 models

NCAR

CCSR

CGCM

CSIRO

ECHAM

GFDL

HadCM
1.3.3 Downscaling GCM output into site-specific surface weather series (representing present & future climate)

1. dynamical downscaling (GCM $\rightarrow$ RCM): Regional Climate Models (RCMs) are more detailed than GCMs, but direct use of RCM output is still unsatisfactory (RCM-based series should be post-processed (I have some slides to document the RCM-OBS misfit…)

2. statistical downscaling (= estimating surface weather with empirical-statistical relationships between
   - larger-scale "free-air" circulation characteristics
   - surface weather

3. our favourite approach: using the weather generator:
   - step 1: WG is calibrated using observed weather series, and
   - step 2: WG parameters are modified according to the GCM-based climate change scenario [CCS = changes in selected surface climatic characteristics (AVG, STD, …), typically for individual months]

1.3.4.1 weather generators: introduction

• task: produce site specific weather series representing future climate…

• WGs are often regarded as one of the SDS techniques…

• similarities with SDS:
  – it relies on statistics (rather than physics-based equations used in GCMs and RCMs)
  – it produces site specific (or area-specific) surface weather series

• differences from SDS:
  – to calibrate WG, you need only observed variables required by the impact model, so that
  – it does not need circulation characteristics (it rather relies on a fact that the circulation regime is inherently reflected in a structure of surface weather series)
  – stress on the stochastic structure of the surface weather series
**1.3.4.2 Statistical Downscaling scheme**

*... to be compared with the following slide*

**1.3.4.3 Weather generator scheme**

*Y = vector of surf. wea. variables
Y\textsubscript{prev} = Y on previous day(s)
e = random vector
P = vector of WG parameters*
use of WG in generating future-climate weather series

Weather generator = mathematical model, which generates synthetic weather series, which are statistically similar to the observed series.

statistical similarity = major statistical features are the same: AVG, VAR, MAX/MIN, annual cycle, correlations between variables, lag-correlations, ...

pros: - arbitrary long wea. series
- may be interpolated
- needs less GCM data
- various characteristics may be modified
- may be used even for climates not simulated by GCM (using pattern scaling method)

con: no WG model is perfect…

Climate change scenario = changes in major climatic statistics (monthly, seasonal, annual); may include changes in Variability

Ex = present "climate"
d(t) = clim.change scenario
Ex' = future climate

part 2

weather generators
**weather generators: how it works**

**example: M&Rfi weather generator**  
(\sim \text{WGEN-like parametric weather generator})

- **M&Rfi weather generator** (\sim \text{Richardson’s WGEN})
  - generates daily time series
  - **4 surface weather characteristics** (though it can do much more…), which are mostly required as an input to the crop growth models (including DSSAT crop models):
    - \textit{PREC, TMAX, TMIN, SRAD}

- each term is generated in three steps:
  1. generation of \textit{precipitation occurrence} \sim \text{1st order Markov chain}
  2. (if the day is wet) generation of precipitation amount: \textit{PRE}C \sim \text{Gamma dist.}
  3. generation of \textit{(SRAD, TMAX, TMIN)} \sim \text{AR(1) model}

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**2.1.1 weather generators: how it works**

**step 1: precip. occurrence \sim \text{Markov chain}**

- let \( P(\text{wet}) = 0.35 \) is a probability of wet day occurrence

- generate random number \( X \) with uniform distribution \( \text{Prob}(X<x) = x; \ x \in <0,1> \)
  - if \( X \leq P(\text{wet}) \) → wet day
  - if \( X > P(\text{wet}) \) → dry day

- to account for the persistence, \( P(\text{wet}) \) may depend on the previous days’ wet/dry status:

\[
P(\text{wet}) = \begin{cases} 
P_{01} & \text{if yesterday was dry} \\
P_{11} & \text{if yesterday was wet} 
\end{cases} \quad \text{Markov chain of 1st order}
\]

\( n \)-order Markov chain account for \( n \) previous days
2.1.2 weather generators: how it works

step 1: precip. occurrence ~ Markov chain

Markov chain generator of wet/dry days:

a) $P_{\text{wet}} = 0.5$ ($= P_{01} = P_{11}$) >>> no persistence!!!

b) $P_{\text{wet}} = 0.5$; $P_{01} = 0.1$, $P_{11} = 0.9$ (strong persistence; 2 realizations are shown):

2.1.3 weather generators: how it works

• step 2: generation of precipitation amount

– assumption: $\text{PREC} \sim \Gamma(a,b)$
2.1.4 Weather generators: how it works

- **step 3: generation of** $X = (TMAX, TMIN, SRAD)$

- **assumption:** $X_i^* \sim N(0,1)$

  where $X_i^*$ is standardized:

  $$X_i^* = \frac{X_i - \text{avg}(X_i)}{\text{std}(X_i)}$$

- **to account for** $X$’s dependence on PREC: avg($X$) & std($X$) are determined separately for wet and dry days

- **to account for the lag-0 and lag-1 correlations,** AR model is used:

  $$X^*(t) = AX^*(t-1) + Be$$

  where $A$ and $B$ are 3x3 matrices, $e$ is a 3D white noise

2.2 Weather generators – main features

- **spatial resolution:**
  - single-site (OK for crop growth model; example: M&Rfi)
  - multi-site or spatially continuous (required in hydrological modelling)

- **temporal resolution (~time step):**
  - hourly
  - daily
  - monthly
  - M&Rfi: optional time step = 1,2,3,5 days, 1w, 10d, 2w, ½mo, 1mo)

- **number of variables**
  - single-variate
  - multi-variate (CERES: 4 vars; WOFOST: 6 vars)
  - M&Rfi: optional (up to 8)

- **conditioning of WG on circulation**
  - **stand-alone surface** weather generator (M&Rfi, WGEN, LARS-WG)
  - conditioned on circulation

- **parametric vs. non-parametric**
  - **parametric:** WGEN, SIMMETEO, M&Rfi
  - **semi-parametric** (Semenov: LARS-WG)
  - **non-parametric** (nearest neighbours resampling)
2.3 parametric weather generators

- structure of the weather series is represented by a model defined by parameters, which are derived from observed series:
  - distributions of variables: Gamma, Gauss, exponential, …
  - persistence and correlations between variables:
    - Markov chains (1st or higher order)
    - autoregressive models
    - annual cycle: Fourier series
- examples: WGEN, Met&Roll, M&Rfi, …

2.4 Nearest neighbours resampling WG

algorithm:

<table>
<thead>
<tr>
<th>learning sample:</th>
<th>synthetic series:</th>
</tr>
</thead>
<tbody>
<tr>
<td>@DATE SRAD TMAX TMIN RAIN</td>
<td>@DATE SRAD TMAX TMIN RAIN</td>
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<td>...</td>
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<td>...</td>
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<td>...</td>
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<td>xx008 3.7 -3.8 -8.0 1.0</td>
<td>...</td>
</tr>
<tr>
<td>xx009 1.7 0.0 -3.9 8.3</td>
<td>...</td>
</tr>
</tbody>
</table>

1. choose the first term: randomly from all terms close to 1st January ± 10 days
2,3,... choose the new term: a) choose term(s), which are close (distance ~ Mahalanobis) to the previous term, b) the new term is a follower of the selected term

PROs: no assumption on distribution of variables

CONs: - much slower (than the parametric model)
       - problem: how to implement climate change scenario?
       - non-interpolable
2.5 semi-parametric WG

- **example:** LARS-WG (by Semenov)
- **main differences from parametric WG:**
  - wet and dry periods modelled by empirical distribution
  - PDFs of variables are not described by parametric distributions, but rather by **empirical distributions**, which represented by a set of **percentiles**
    - (23 used in LARS-WG; compare with 2 parameters for Normal or Gauss)
- **PRO** (wrt parametric WG): better treatment of non-normal variables
- **CON:** size of the learning sample is **more critical** ← more parameters are determined from the learning data

**references:** Semenov + his web page, ...

2.6 conditioning WG on circulation

1. **learning time series:** \{WT(i), Y(i)\}_i=1..n
2. **calibration of WG** from the L.series:
   - f(X|WT)
   - parameters of WT time series
     - transitional probabilities (if we use set of weather types to characterize circulation)
     - parameters of AR model (if the circulation pattern is characterised by PC scores)
3. **applying WG**:
   a) generation of WT series
   b) generation of surface wea. series

**PRO:** circulation is explicitly involved
**CON:** we need future GCM simulation to calibrate the WG's circulation component > limited possibilities for uncertainty analysis

**references:** Bardossy, ...

\[ X \sim \text{empirical PDF} \]
now, back to M&Rfi

... is freely available on web:
www.ufa.cas.cz/dub/wg/marfi/marfi.htm

2.7.1 M&Rfi – history (M&Rfi = Met&Roll flexible and improved)

- *1995:* first version of Met&Roll (~ WGEN) to be used with CERES crop models

- since 1995: improvements of the model
  – Markov(1) > Markov(3)
  – conditioning on monthly WG

- 2005-2007: interpolation
- 2007: M&Rfi developed from Met&Roll (thanks to Juergen Grieser’s initiative & FAO)
  – many new features with respect to Met&Roll (on a separate slide)

- Met&Roll / M&Rfi applications:
  - crop growth modelling (together with MUAF)
    - climate change impact studies
    - probabilistic seasonal crop yield forecasting -> PERUN system /2001/)
    - climate change impacts on soil climate, pests & diseases, …
  - hydrological modelling
  - 2009: linked with WABAL (thanks to CNR-Ibinet Sassari, P.Zara)
2.7.2 Met&Roll / M&Rfi : model

- **Met&Roll** = 4-variate stochastic daily weather generator:

  step 1: PREC occurrence ~ Markov chain (order: 1-3; parameters: trans.prob.)

  \[
  \text{Prob}(\text{PREC}(t)>0) = \begin{cases} 
  P01 \text{ if PREC}(t-1) = 0 \\
  P11 \text{ if PREC}(t=1) = 1 
  \end{cases}
  \]

  step 1b (only if PREC(t)>0) :

  PERC. amount ~ Gamma distribution (parameters: \(\alpha\), \(\beta\)  \(\sim\) shape, scale/)

  step 2: \(X = (X_1, X_2, \ldots) \sim \text{AR}(1)\) model (parameters: \(A\), \(B\), \(\text{avg}(X_i)\), \(\text{std}(X_i)\))

  \[X^*(t) = AX^*(t) + Be\]

  where

  \(X_i = [\text{SRAD}, \text{TMAX}, \text{TMIN}]\)
  \(X^*_i = [X_i - \text{avg}(X_i)] / \text{std}(X_i)\)
  \(\text{avg}(X_i)\) and \(\text{std}(X_i)\) differ for sry / wet days
  \(e = \text{white noise}\)
  \(A, B = [3x3] \text{ matrices}\)

- all parameters are assumed to vary during the year
- daily WG is linked to AR(1)-based monthly WG (to improve low-frequency variability)

2.7.3 M&Rfi – main features

- !!! run via command line !!!

- optional **number of variables** (<=8) [typically 3 or 4: (PREC, SRAD, (TMAX + TMIN) or (TAVG + DTR) or TAVG)]
- optional **time step** (1d, 3d, 5d, 1w, 10d*, 2w, \(\frac{1}{2}\)m, 1m)
- 1 variable (PREC) is optionally “the conditioning variable”
- transformation of variables
  \(\rightarrow\) may better treat non-normal variables (allows parametric & non-parametric transformations) \(\rightarrow\) VAPO and WIND are first candidates for inclusion
- estimation of solar radiation from cloudiness or sunshine
- estimation of evapotranspiration using Penman-Monteith equation
- more user-friendly (guide available)
- run via **command line** [~M&R]
- all WG parameters stored in a single file, more stations may be stored in a single file
- the synthetic weather series may be “forced” to fit [~M&R]
  – **weather forecast** for a forthcoming period (following days, month or whole season)
  – **climate change scenario** (including changes in both high-frequency and low-frequency variability)
    - through modifying WG parameters
    - through direct modification of input weather series
### 4-variate → 6-variate
(nearest neighbours resampling)

**4-variate series:**
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**Learning sample:**
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**6-variate series:**
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```

---

### 2.7.4

**testing quality of the weather generator**

*motivation: WG cannot perfectly fit the structure of the real-climate weather series*

**direct validation**
- comparison of observed vs. synthetic weather series in terms of derived climatic characteristics *(synthetic series should resemble observed series)*

**indirect validation**
- comparison of characteristics derived from model output (e.g. crop growth model) fed by OBS and SYNT weather series *(outputs from impact model fed by OBS and SYNT wea.series should resemble each other)*
2.8.1  scheme of WG validation

obs.wea.series  
(~15-30 years...)

WG (present climate)

synt.weather series  
(present climate)

calculation of selected climatic characteristics

B: direct validation of WG: comparison of weather statistics from OBS vs SYNT
C: indirect validation of WG: comparison of output from impact model fed by OBS vs SYNT weather series

CROP GROWTH MODEL

model “yields”  
(obs.wea.)

model “yields”  
(synt.wea: “presence”)

info about  
- plant genetics
- soil properties
- growing site
- management

B. normality of SRAD, TMAX, TMIN:

variability of monthly means:

length of dry periods:

2.8.2  Met&Roll - direct validation
Motivation:

How the WG imperfections (to fit the structure of real-world weather series) affect output from impact models fed by synthetic series?

---

crop model: CERES-Wheat; 30-y simulations for 17 Czech stations
weather generator:
- WG-BAS: “basic” WG: no annual cycle of AR matrices; 1\textsuperscript{st} order Markov chain
- WG-A3: improved WG: annual cycle of AR matrices; 3rd order Markov chain
interpolation of Met&Roll weather generator
(
(calimaro project)

• 2005-2007

• 4 Czech institutes (9 people) participated

• Main aim: interpolation of Met&Roll parameters
  – motivation: applicability of Met&Roll for sites without observations

• sub-aims:
  1. choice of the interpolation methods
  2. validation in terms of the climatic characteristics
  3. validation in terms of outputs from models fed by synthetic series produced by the interpolated generator
     • crop model
     • hydrological rainfall-runoff models

2.9.1 WG interpolation: DATA + REGION

- Station weather data: 125 stations from Czechia
  a) circles: “learning” set, b) squares: “validation” set
- Topography is derived from the global digital elevation model GTOPO30 (0.5x0.5’)
- altitude varies from 115 to 1602 m a.s.l.
2.9.1 Scheme: Testing interpolated weather generator

WG parameters:

Daily weather series (125 st.):

Impact model (crop-growth model, hydrological model, ...)

Output from impact models:

2.9.2 1) choice of the interpolation technique

1) co-kriging (used via ArcGIS)

2) neural networks [Multilayer Perceptron network type = 3-5-1, 29 degrees of freedom, Back Error Propagation and Conjugate Gradient Descent training algorithms used]

3) weighted nearest neighbours
   \[ y(x,y,z) = \text{weighted average from the surrounding stations (d<100km; bell-shaped weight function) corrected for the zonal + meridional + altitudinal trends} \]

+ WG parameters mapped using GTOPO30 digital elevation map (0.5x0.5')
2.9.3 interpolated WG:
validation in terms of WG’s precipitation parameters

Nearest Neighbors interpolator was found the best and selected for the additional experiments (Box 2 and Box 3)

2.9.4

2) validation in terms of extreme precipitation characteristics

- only NearestNeighb. and NeuralNetwork -
2.9.4.1 Annual max. length of dry spell

- **B(int)**: ............. WG underestimates max. length of dry spell (the fit is better if MC3 model is used)
- **B(int)**: ............. interpolated WG performs similarly as the site-calibrated WG
- **B(int)**: ............. both interpolation techniques perform similarly
- **B(wg) vs B(int)**: differences due to interpolation are lower than those due to WG imperfections

2.9.4.2 Annual max. length of wet spell

- WG simulates dry spell better than the dry spells
2.9.4.3 **Annual max. 1day precipitation**

- **B(wg)**: WG underestimates annual extreme precipitation
- **B(wg) vs B(int)**: differences due to interpolation are lower than those due to WG imperfections

2.9.4.4 **Annual max. 5-day precipitation**

Similar as 1-day PREC but even more pronounced:
- **B(wg)**: WG underestimates annual extreme precipitation
- **B(wg) vs B(int)**: differences due to interpolation are lower than those due to WG imperfections
2.9.4 Annual extreme precipitation characteristics - summary

B\((wg) vs B\(int\): differences due to interpolation are lower than those due to WG imperfections

2.9.4 30-year extreme precipitation characteristics - summary

Results are similar as in the case of the annual extremes
2.9.5

Czechia vs. Nebraska

Czechia
- area = 78864 km²
- 125 stations available (squares: CZ-25 subset)
- 1961-1990

Nebraska
- area = 200520 km²
- 25 stations
- 1988-2006

→ 12.7 times higher density of stations (in this experiment) in Czechia

Main results:
• CZ and NE: differences due to interpolation are lower than those due to WG imperfections
• performance of interpolated WG is similar in CZ and NE

2.9.5

L(Dry) (mean annual maximum)

- the differences are due to WG imperfections
- the differences are due to imperfections in interpolation
2.9.5 **PREC-1d** (mean *annual* maximum)

- the differences are due to WG imperfections
- the differences are due to imperfections in interpolation

2.9.5 **TMAX** (mean *annual* maximum)

- the differences are due to WG imperfections
- the differences are due to imperfections in interpolation
Motivation:

We have found imperfections in reproducing climatic characteristics by interpolated WG (previous slides).

Q: How these imperfections affect output from crop model (or any other model) fed by weather series produced by the interpolated WG?

Scheme: Testing interpolated weather generator

WG parameters:

Daily weather series (125 st.):

Climatic characteristics:

Output from impact models:

Accuracy of interpolation: $A(int)$

Ability of WG to reproduce climatic characteristics: $B(wg)$

Effect of interpolation of WG on climatic characteristics in synt. series: $B(int)$

Effects of WG inaccuracies on impact models output: $C(wg)$

Effect of interpolation of WG on impact models output: $C(int)$
2.9.6 interpolated WG: Indirect validation via STICS model AVG(model wheat yields) [soil = Chernozem (CZ_01)]

- **A:** yields simulated with observed weather
- **B:** interpolated yields
- **C:** yields simulated with site-calibrated WG
- **D:** yields simulated with interpolated WG

- **B** vs **A:** differences due to interpolation of model yields
- **C** vs **A:** differences due to WG imperfections
- **D** vs **A:** differences due to WG imperfections and WG interpolation

**M&Rfi: effect of time step** [Dubrovsky and Grieser 2007, EGU]

- **Experiment:**
  - 8 European + 11 US stations
  - 3 versions of M&Rfi: dT = 1 day, 10 days, 1 month
  - each station:
    o 1 observed series
    o 30 synthetic series for each of 3 WGs

- **Result:**
  - the best performance in reproducing monthly variability is obtained by monthly WG
Climate change scenarios

focus on uncertainties

3.1 the most straightforward way in developing
Climate Change Scenario: DELTA approach

• **climate change scenario** defines changes in climatic characteristics
  
• **It is mostly derived** as a difference (or ratio) for the climatic characteristics:

  \[ \text{CCscenario} = \Delta \text{MEANS} \]

• commonly:
  - variability
  - Prob(wet day occurrence)
  - other parameters, e.g.
    - Gamma dist. pars.
3.2.1 Cascade of uncertainties in developing regional climate change scenarios

1. emission scenario
   - carbon cycle & chemistry model
2. concentration of GHG and aerosols >> radiation forcing
   - GCM
3. large-scale patterns of climatic characteristics
   - downscaling
4. .....................................site-specific climate scenario

3.2.2 Our aim in climate change impact studies:
probabilistic assessment reflecting existing uncertainties (…at least some of them)

For this, we need scenarios from

several emission scenarios  X  several GCM runs

(GCMs: various models, various settings, various realisations)

• ... but: GCM simulations need huge computer resources
  - >> only limited number of GCM simulations available
  - >> GCM simulations do not cover existing uncertainties in emissions, climate sensitivity)

• so, to account for the uncertainties, we may use:
  – http://www.climateprediction.net
  – pattern scaling, which separates global and regional uncertainties
3.2.3 Global temperature growth at SRES-A2: 11 GCMs (colour time series) vs MAGICC model run at various climate sensitivities; yellow bar on the right)

Range of $\Delta T_{\text{glob}}$ simulated by a set of GCMs is not representative for the uncertainty in climate sensitivity → “pattern scaling” method helps

3.3.1 pattern scaling technique

allows to separate 2 uncertainties:

1. the pattern of change ← GCM

2. “global magnitude of change” ($\Delta T_{\text{glob}}$ being a result of emission scenario and clim.sensitivity) ← MAGICC
3.3.2 pattern scaling technique

**assumption:**
- pattern (spatial, annual cycle) is constant
- magnitude changes proportionally to $\Delta T_{\text{Glob}}$:

\[
\Delta X(t) = \Delta X_S \times \Delta T_G(t)
\]

where $\Delta X_S$ = standardised scenario (= scenario related to $\Delta T_G = 1 \, ^\circ\text{C}$)

a) $\Delta X_S = \Delta X_{[tA-tB]} / \Delta T_G [tA-tB]$

b) linear regression $[x = \Delta T_G; y = \Delta X]$

$\Delta T_G = \text{change in global mean temperature}$

!! $\Delta T_G$ may be estimated by other means than GCMs!!
(e.g. simple climate models /~ MAGICC/)

3.3.3 pattern scaling technique

- standardised change of clim.characteristic $X$ determined by linear regression and coincides with the slope parameter in reg.eq.: $\Delta X = a \ast \Delta T_{\text{globe}} + b$

the present example: $\Delta TEMP_S = 1.17; \Delta PREC_S = -0.0075 (-0.3\%)$

the low correlation with $T_{\text{globe}}$ ($R^2$) may indicate large role of natural variability
validity of pattern scaling

- TEMP: well correlated with $T_{\text{GLOB}}$
- PREC, DTR, SRAD, VAPO, WIND: lower correlation with $T_{\text{GLOB}}$
  - natural variability dominates?
  - ..... this may be simulated by WG

• be careful with extrapolation!
  (smoothing annual cycles may help)

Variance of grid-specific TEMP and PREC changes explained by the pattern scaling technique
(averaged over 12 monthly values)

3.4.1 Uncertainties in standardised climate change scenarios (~ pattern of change)
[scenarios for the Czech Republic]

Experiment:
- 7 AOGCMs (1961-2099, emissions ~ IS92a / bau / 1%CO2-per-year)
- 4 weather elements: $T_{\text{AVG}}$, DTR, PREC, SRAD
- 4 exposure units – in Czechia
- 4 uncertainties in the scenario pattern compared:
  1. inter-model uncertainty (7 GCMs)
  2. internal GCM uncertainty (4 runs of HadCM2) (~ natural climatic variability)
  3. choice of the site (4 sites in Czechia)
  4. uncertainty in the standardised changes (~ std. error in regress. coefficients)

(Dubrovsky et al., 2005, Climate Research)
3.4.2 IPCC-AR2: grid structure of GCM models

\[ \Delta X = 2.8 - 7.5^\circ; \ \Delta Y = 2.5 - 5.6^\circ; \ Nz = 9 - 20 \ (hladin) \]

3.4.3 4 uncertainties in climate change scenario:

**TAVG** (avg ± std)

- compare the 4 uncertainties!
3.4.4 uncertainties in climate change scenario:
PREC (avg ± std)

- compare the 4 uncertainties!

3.5 "between IPCC-AR" uncertainties in standardised scenarios for CR

PRECC-AR2

PRECC-AR3

PRECC-AR4

TEMP
uncertainties in scenarios from IPCC-AR4 database

--- Europe ---

[presented at EGU2009]

3.6.1

scenarios from AR4 models

[presented at EGU2009]

list of 18 / 14 GCMs used in the analysis:

<table>
<thead>
<tr>
<th>center</th>
<th>model</th>
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<th>SRES-A2</th>
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AR4 GCMs: validation & scenarios

Annual cycle of the GCM-based 1961-90 means (regridded into the CRU’s 0.5° × 0.5° grid) vs CRU gridded climatological means (TS2.1 dataset)

Temperature is validated in terms of: BIAS, RV, RMSE
Precipitation is validated in terms of: %BIAS, RV, %RMSE

where:

BIAS = avg(GCM) – avg(CRU) (*)
%BIAS = 100 × BIAS / avg(GCM) (*)
RV = Reduction in Variance (indep. variable = CRU monthly means; dep. variable = debiased GCM monthly means)
RMSE = root mean square error (debiased GCM monthly means vs CRU monthly means)
%RMSE = 100 × RMSE / avg(GCM) (*)

(*) avg(X) is an average of 12 monthly values (in validation of the annual cycle)

3.6.3.1 GCMs vs CRU (1961-90 monthly means)

RMSE (annual cycle of TAVG)
3.6.3.2 GCMs vs CRU (1961-90 monthly means)

RV (annual cycle of TAVG)

3.6.3.3 GCMs vs CRU (1961-90 monthly means)

RMSE (annual cycle of PREC)
3.6.3.4 GCMs vs CRU (1961-90 monthly means)

RV (annual cycle of PREC)

3.6.4 scenarios from 7 GCMs (IPCC-AR3; SRES-A2; (2070-99) vs (1991-2020))

- BCM2
- CGHR
- CGMR
- CNCM3
- CSMK3
- ECHOG
- GFCM20
- GIAM
- HADCM3
- HADGEM
- INCM3
- INGSXG
- MIHR
- MIMR
- MPEH5
- MRCGCM
- NCCCSM
- NCPCM

- CSIRO
- CGCM
- ECHAM
- GFDL
- HadCM
- CCSR
- NCAR
motivation: to show the multi-model mean/median + uncertainty in a single map

step1: results obtained with each of 7 GCMs are re-gridded into 0.5x0.5° grid (~CRU data)

step2: median [\text{med}(X)] and \text{std} [\text{std}(X)] from the 18/14 values in each grid box are derived

step3 (map): the median is represented by a colour, the shape of the symbol represents value of uncertainty factor \( Q \):

\[
Q = \frac{\text{std}(X)}{\text{med}(X)}
\]

interpreting the uncertainty:

- squares and circles [\text{std}(X) \leq 0.5 \times \text{median}(X)] indicate that \text{med}(X) differs from 0 at significance level higher than 95% (roughly)

- 4-point stars indicate high uncertainty [\text{std}(X) > \text{med}(X)]

or: the greater is the proportion of grey (over sea) or black (over land) colour, the lower is the significance, with which the median value differs from 0

3.6.5.2

18-GCM validation of annual cycle (median [~colour] and STD [~symbol] of 18 GCMs)

- note that annual cycle of PREC is reproduced much worse by GCMs
3.6.5.3 14-GCM standardised scenario – $\Delta T_{AVG}$ (SRES-A2)

nearly whole Europe: $\text{STD}(\Delta T) < 0.4 \times \text{median}(\Delta T)$

3.6.5.4 14-GCM standardised scenario – $\Delta \text{PREC}$ (SRES-A2)

!!! $\text{STD} > 2 \times \text{median} !!!
1) validation of the annual cycle

- GCMs better fit TEMP then PREC
- **TEMP**: good performance + good between-GCM fit in Central+W.Europe, incl. UK
- **PREC**: good performance + good between GCM concordance in:
  - west.UK
  - Norway+Finland
  - Portugal
  + parts of the Mediterranean
- **RV** & **RMSE** provide different patterns

2) standardised scenario:

- **TAVG** perfectly correlated with $T_globe$
- **PREC**: lower correlation with $T_globe$
  - regional & seasonal patterns
  - lowest correlation along 50th parallel
  - low correlations with $T_globe$ (and large between-GCM differences) are assumed to be due to low climate change signal (natural climate variability dominates)

**be careful with extrapolation!**
*(don’t scale std.scenarios with large $\Delta T_globe$)*
3) CC scenario for Europe:
• TAVG increases everywhere during the whole year; largest increases in S.Eu. (summer) and NE Eu. (autumn)

• PREC: decreasing in South and increasing towards North (note the nice zonal pattern in changes in annual PREC)

• Mediterranean: significant PREC decrease in spring and summer ➔ drought risks will increase

• North: increased temperature is accompanied by PREC increase

• SRES-A2 vs SRES-A1b: little differences between standardised scenarios

WG-friendly climate change scenarios

( = scenario in terms of WG parameters)

(presented at EMS/ECAC 2008)
3.7.1

WG-friendly climate change scenarios

**GCMs** (run at SRES-A2 emission scenario; simulations for the IPCC-AR4)

<table>
<thead>
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<th>Acronym</th>
<th>Model</th>
<th>Center</th>
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<td>1961-90</td>
<td>2081-2099</td>
</tr>
</tbody>
</table>

A: 3 runs available

3.7.2

WG-friendly climate change scenarios

- present experiment -

- **Scenarios of changes in WG parameters for several European cities** are derived from daily output of several GCMs.

- **Climate change scenario** = future-climate vs present-climate WG parameters. *(difference in the case of temperature; ratio in the case of STDs and PREC)* ratio. WG parameters are derived from detrended time series (within given time slice).

- **Climatic characteristics shown here:**
  - $d[TAVG]$: change in the mean daily temperature
  - $d[DTR]$: change in the daily temperature range ($DTR = TMAX - TMIN$)
  - $d[PREC]$: change in precipitation amount
  - $d[std(TAVGday)]$: change in standard deviation of daily average temperature
  - $d[std(TAVGmonth)]$: change in STD of monthly average temperature;
  - (changes in STD are calculated from detrended TAVG series)

- **Sampling errors in scenarios** (shown for Prague) are estimated from 10 scenarios derived from 10 pairs of synthetic present-climate and future-climate weather series generated by M&Rfi calibrated from the GCM series.
3.7.3
WG-friendly climate change scenarios
Rome

3.7.4
WG-friendly climate change scenarios
Prague
Creating a set of climate change scenarios for impact analysis

To reflect above uncertainties, we typically use a combination of $3 \Delta T_G \times 3$ GCMs:

- **Uncertainty in $\Delta T_G$ (modelled by MAGICC):**
  - High scenario: SRES-A2, 4.5 K
  - Low scenario: SRES-B1, 1.5 K
  - Middle scenario: Middle, 2.5 K

- **Uncertainty in pattern:**
  - Set of GCMs
  - Preferred GCMs:
    - HadCM3
    - NCAR-PCM
    - ECHAM5

+ Natural variability (day-to-day, year-to-year) is modelled by WG
3.9 stochastic scenario generator

3.9.1 stochastic scenario generator: model

1. construction of scenarios from GCM

2. construction of “scenario series”

3. calibration of the scenario generator’s model
   [parameters: \( \text{avg}(X|m), \text{std}(X|m), \text{COR}(X_i,X_j), \text{COR}(X_m,X_{m-1}) \)]

4. generation of synt. “scenario series”

5. construction of synthetic scenarios
3.9.2 stochastic scenario generator: validation

**annual AVG(TEMP)**

ANNUAL AVG (Tmonth) [deg C]

![Graph showing annual average temperature for EU and US regions with 11 GCMs and cliM&Tess for present climate.]

3.9.3 stochastic scenario generator: validation

**annual MIN(TEMP)**

ANNUAL MIN (Tmonth) [deg C]

![Graph showing annual minimum temperature for EU and US regions with 11 GCMs and cliM&Tess for present climate.]

11 GCMs

present climate
### 3.9.4 Stochastic Scenario Generator: Validation

#### Annual Max(TEMP)

![Graph showing annual max temperature across Europe and the USA with 11 GCMs and present climate data.]

#### Annual Avg(PREC)

![Graph showing annual average precipitation across Europe and the USA with 11 GCMs and present climate data.]

**New**

- MIN(TEMP)
- MAX(TEMP)
- AVG(PREC)
3.9.6 stochastic scenario generator: validation

**annual MIN(PREC)**

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<th>Station</th>
<th>Value</th>
</tr>
</thead>
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<td>VALT</td>
<td>9.0</td>
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<tr>
<td>ZUGS</td>
<td>10.0</td>
</tr>
</tbody>
</table>

**Europe**

**U.S.A.**

3.9.7 stochastic scenario generator: validation

**annual MAX(PREC)**

<table>
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<tr>
<th>Station</th>
<th>Value</th>
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</tr>
<tr>
<td>ZUGS</td>
<td>13.0</td>
</tr>
</tbody>
</table>

**Europe**

**U.S.A.**
Experiments focused on: TAVG, PREC, Z-index, PDSI
- annual AVG, MIN and MAX were determined from
  - 100y synthetic weather series representing present climate
  - 11x100y synthetic weather series (11 GCMs)
  - 10x(11x100y) synthetic weather series (10x11 scenarios)

Quality of the scenario generator (cliM&Tess vs 11 GCMs):
- scenario generator works well for AVG(TEMP) (means, variability and 90y extremes are very close to the values obtained with a set of GCM-based scenarios)
- worse, but still satisfactory fit is obtained for annual MAX / MIN of TEMP and for PREC characteristics: the range between 90-year maxima and minima is mostly overestimated by the scenario generator. The avg±std’s are, however, mostly satisfactorily reproduced by the generator
- even worse misfit is manifested for Z and PDSI drought indices: not only extreme values, but also avg±std are affected.

Climate change impacts (11 GCMs vs Present climate) (wasn’t main aim of this analysis):
- temperature: increase at all stations
- precipitation: insignificant changes or slight decrease at most stations
- drought: significant increase of drought risk at all stations

Conclusions
Conclusions: WG + pattern scaling

- weather series(future) = \( \text{WG} [\text{PAR(OBS)} \times \text{CCS(GCM)}] \)
  where
  \- WG = M&Rfi
  \- CCS (climate change scenario)
    \- includes changes in means and variability (daily and monthly)
    \- is determined by the pattern scaling technique:
      \( \text{CCS} = \text{CCS}^*(\text{GCM}) \times \Delta T_g(\text{MAGICC} (\text{clim.sens.,emis.scen})) \)

- the methodology accounts for several uncertainties:
  \- between-GCM differences \( \leftrightarrow \) using several GCMs
  \- uncertainties due to clim. sensitivity and emission scenario \( (\text{by using several } \Delta T_g \text{ values modelled by MAGICC}) \)
  \- natural variability \( \leftrightarrow \) stochasticity of WG

- other advantages of using WG:
  \- may generate arbitrarily long weather series
  \- easy to modify selected parameters \( > \) good for sensitivity studies
  \- may be interpolated (to generate series for sites without observed data)

Conclusion - What I can provide:

- Weather Generator
  \- now available:
    \- daily / dekadal / monthly single site multi-variate weather generator (M&Rfi)
    \- may be interpolated into any site (to be completed!)
    \- linkable to GCM-based climate change scenarios
    \- output format fits various impact models (WOFOST, WABAL, …)
  \- to be done:
    \- finetune dekadal WG
    \- resolve problems with wind and humidity
    \- implement interpolation (by now, Met&Roll was interpolated)

- Climate Change Scenarios
  \- GCM-based scenarios produced by pattern scaling method:
    \- set of GCMs \( (\text{e.g. IPCC-AR4 dataset}) \) may account for inter-GCM uncertainties
    \- scaling by \( \Delta T_g \) \( (\text{estimated by MAGICC}) \) accounts for uncertainties in
      \- emission scenario
      \- climate sensitivity
    \- now available: changes in AVG and STD of TEMP, SRAD, PREC
    \- to be completed: wind and humidity
  \- climate change scenario generator: now under development
std. scenario - (14 GCMs, SRES-A2)

\[ \Delta TAVG \]
\[ \Delta PREC \]

spring
summer
autumn
winter
year

find more (incl. conference presentations & selected papers):

www.ufa.cas.cz/dub/crop/crop.htm