# Impacts of recent drought and warm years on water resources and electricity supply worldwide

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**Abstract**

Recent droughts and heatwaves showed the vulnerability of the electricity sector to surface water constraints with reduced potentials for thermoelectric power and hydropower generation in different regions. Here we use a global hydrological-electricity modelling framework to quantify the impacts of recent drought and warm years on hydropower and thermoelectric power usable capacity worldwide. Our coupled modelling framework consists of a hydrological model, stream temperature model, hydropower and thermoelectric power models, and was applied with data of a large selection of hydropower and thermoelectric power plants worldwide. Our results show that hydropower utilisation rates were on average reduced by 5.2% and thermoelectric power by 3.8% during the drought years compared to the long-term average for 1981-2010. Statistically significant ($p<0.01$) impacts on both hydropower and thermoelectric power usable capacity were found during major drought years, e.g. 2003 in Europe (-6.6% in hydropower and -4.7% in thermoelectric power) and 2007 in Eastern North America (-6.1% in hydropower and -9.0% in thermoelectric power). Our hydrological-electricity modelling framework has potential for studying the linkages between water and electricity supply under climate variability and change, contributing to the quantification of the "water-energy nexus".

## 1. Introduction

Droughts can impact electricity supply, in terms of both water availability for hydropower generation and cooling water usage for thermoelectric (e.g. nuclear, fossil-, biomass-fuelled) power generation. At present, hydropower and thermoelectric power contribute 17% and 81% of world's total electricity generation, respectively (EIA, accessed 2015). Recent droughts and heat waves showed the vulnerability of the electricity sector to surface water constraints with reduced potentials for thermoelectric power (Förster & Lilliestam, 2010) and hydropower generation (Kuusisto, 2004). This has shown to be problematic in particular when peak electricity demands are high (e.g. from air conditioning). Potential increases in the severity of streamflow droughts (e.g. Prudhomme *et al.*, 2014, Trenberth *et al.*, 2014) and heatwaves (e.g. Christidis *et al.*, 2015) under changing climate will therefore directly impact energy security.

Impacts of recent droughts on the hydropower and thermoelectric power sector have mainly been studied for parts of the United States (NETL, 2009a, NETL, 2009b) and for European countries (e.g. Fink *et al.*, 2004, IAEA, 2004, Rübbelke & Vögele, 2011), showing a reduced reliability of the power supply system. Limited power supply combined with increased generation costs during droughts and heatwaves can have substantial economic impacts, such as significant rises in electricity prices (Boogert & Dupont, 2005, McDermott & Nilsen, 2014, Pechan & Eisenack, 2014). Most of these studies focused on individual countries or states, while the geographic distribution of droughts and heatwaves often exceeds country and state levels. Therefore large-scale studies and modelling tools to perform such assessments are needed to understand the impacts of water constraints on water-dependent power generation.

While integrated assessment models (IAMs) are powerful tools for large-scale energy studies (e.g. GEA, 2012, van Vuuren *et al.*, 2012), most IAMs are developed for scenario analyses, providing output at coarse spatial and temporal resolutions and do not yet include detailed processes that incorporate regional or local impacts of water constrains on power supply (Clarke *et al.*, 2014). At present, coupled hydrological-electricity modelling approaches are therefore more suitable for

44    studying the impacts of water constraints during historical and future droughts and warm events (e.g.

45    Pereira-Cardenal *et al.*, 2014). However, a limited number of studies have analysed these impacts on

46    electricity supplies at the large scale.

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48    Here we show the impacts of recent drought and warm years on both hydropower and thermoelectric

49    power usable capacity in regions worldwide. We used a hydrological-electricity modelling framework

50    which was applied to 24,515 hydropower plants and 1,427 thermoelectric power plants worldwide

51    (section 2.1). We identified critical years with streamflow drought and high water temperature and

52    quantified to what extent hydropower and thermoelectric power capacity were impacted during these

53    drought, warm years in different regions (section 2.2 and section 3). In addition, we discuss the main

54    uncertainties and usability of these results for large-scale management of the electricity sector (section

55    4).

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58    **2. Methodology**

59    *2.1 Hydrological-electricity modelling*

60    We used a coupled hydrological-electricity modelling framework consisting of a hydrological model,

61    stream temperature model, hydropower and thermoelectric power models, which is described in van

62    Vliet *et al.* (2016). This modelling framework focuses on the physical impacts of water constraints

63    under climate variability on power plant usable capacities. Impacts of land use changes and economic

64    feedbacks of the assessed water constraints (e.g. supply-demands portfolio, electricity prices) are not

65    modelled. The hydrological component consists of the Variable Infiltration Capacity (VIC) model

66    (Liang *et al.*, 1994), which is a grid-based macro-scale hydrological model that solves both the surface

67    energy and water balances. The reservoir scheme of Haddeland *et al.* (2006) which is combined with

68    the routing model of Lohmann *et al.* (1998) was used to include reservoir impacts on streamflow. This

69    scheme assumes that reservoir operations follow simple operational rules based on the purpose(s) of

70    dams (Haddeland *et al.*, 2006). The water temperature component of our modelling framework consist

71    of the physically-based stream temperature river basin model (RBM), which solves the 1D-heat

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72   advection equation (Yearsley, 2009, Yearsley, 2012). RBM was previously modified for application

73   on a worldwide level and to include effects of heat effluents from thermoelectric power plants and

74   reservoir impacts on water temperature (van Vliet *et al.*, 2012a, van Vliet *et al.*, 2012b).

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76   Hydropower usable capacity for each hydropower plant was simulated based on regulated streamflow

77   simulations from VIC, hydraulic head, total efficiency of the power generating unit, density of fresh

78   water and the gravitational acceleration (see supplementary section 1). Thermoelectric power usable

79   capacity was quantified using the model of Koch and Vögele (2009), which was modified as described

80   in van Vliet *et al.* (2012b). This model simulates the required water demand for cooling and usable

81   capacity based on, amongst others, simulated streamflow and water temperature at the thermoelectric

82   power plant site, both the total efficiency and electric efficiency, various parameters related to the

83   cooling system type and environmental limitations for cooling water use (i.e. maximum river

84   temperature (increase) and fraction of streamflow to be withdrawn). The model equations for

85   calculating hydropower usable capacity and thermoelectric power usable capacity are presented in the

86   supplementary section 1. For details of the coupled modelling framework and input datasets we refer

87   to the supplementary information of van Vliet *et al.* (2016).

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89   We used the global Watch Forcing Data Era Interim (WFDEI) meteorological dataset (Weedon *et al.*,

90   2014) as input into the VIC hydrological model and RBM stream temperature model to produce

91   simulations of daily streamflow and water temperature on 0.5°x0.5° spatial resolution worldwide for

92   the period of 1979-2010 (including two years spin-up period). The modelling estimates of streamflow

93   and water temperature were evaluated using observed station records of daily streamflow and water

94   temperature worldwide, which showed a realistic representation of the observed conditions (see

95   supplementary information of van Vliet *et al.* (2016) for a general overview of the model performance

96   and supplementary figure S1 for more detailed results for selected stations).

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98   We applied the hydropower and thermoelectric power models on the plant individual level and

99   extracted daily simulated streamflow and water temperature for 1981-2010 for the grid cell in which

100    each power plant is situated. An evaluation of the impacts of biases (uncertainties) in simulated

101    streamflow and water temperature on usable power plant capacity showed moderated impacts for most

102    of the hydropower plants and thermoelectric power plants included in the uncertainty analysis (see

103    supplementary section 2.3, supplementary table S1 and supplementary figures S3-S5).

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105    We obtained information of power plant characteristics from the World Electric Power Plant Database

106    (WEPPD) version 2013 (UDI, 2013). The latitude and longitude of each power plant, hydraulic head

107    for hydropower plants and water temperature limitations for thermoelectric power plants were derived

108    as described in the supplementary information of van Vliet *et al.* (2016) along with a quantification of

109    the uncertainties in deriving these parameter estimates. For hydropower, we focused on conventional

110    plants. For thermoelectric power we selected plants with availability of information on cooling system

111    type, installed capacity, source of fuel, and use of river water for cooling. In total 24,515 hydropower

112    plants and 1,427 thermoelectric power plants are included (figure 1), which contribute to 78% of the

113    installed hydropower capacity and 28% of the installed thermoelectric power capacity worldwide as

114    reported by the Energy Information Administration (EIA, accessed 2015). This smaller percentage for

115    thermoelectric power is because more information for power plant characteristics (e.g. related to

116    cooling system) is needed to parametrize the thermoelectric power model than for the hydropower

117    model. The geographic distribution and age distribution of the selected plants was found to be

118    representative for the full thermoelectric and hydropower power plant portfolio (see supplementary

119    information of van Vliet *et al.* (2016)). Simulations of hydropower and thermoelectric power were

120    previously evaluated using observed records on the country level for 1981-2010 (EIA, accessed 2015).

121    This showed that the interannual variability was slightly overestimated for some African countries, but

122    for most countries worldwide the observed trends were realistically represented (see supplementary

123    information of van Vliet *et al.* (2016) for a general overview of the model performance and

124    supplementary figure S2 for simulated and observed time series of selected countries).

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127 *2.2 Hydropower and thermoelectric power during recent drought and warm years*

128 We used the gridded simulations of streamflow and water temperature to identify critical years with

129 streamflow drought and high water temperature over 1981-2010. We quantified on a gridcell basis the

130 mean number of days per year with streamflow smaller than the 10-percentile streamflow value, which

131 is a widely used index for extreme low flow (Pyrce, 2004, Smakhtin, 2001, Tharme, 2003). For water

132 temperature, we quantified the number of days per year with values higher than the 90-percentile

133 water temperature over the period 1981-2010. In addition, we calculated the number of days that both

134 low flow and high water temperature coincide. As streamflow droughts and high water temperature

135 events overall occur on a smaller geographic level than continental scale, we aggregated results over

136 all gridcells per subregion to identify critical drought and warm years. We used the subregions defined

137 by Giorgi and Francisco (2000) and adapted by Sheffield and Wood (2007). We focused our analyses

138 of impacts of recent drought and warm years on 12 subregions with the highest number of hydropower

139 and thermoelectric power plants and installed capacity according to the used plant dataset (figure 1).

140 These 12 subregions together comprise 90% of the hydropower plants (n=22,141) and 93% of the

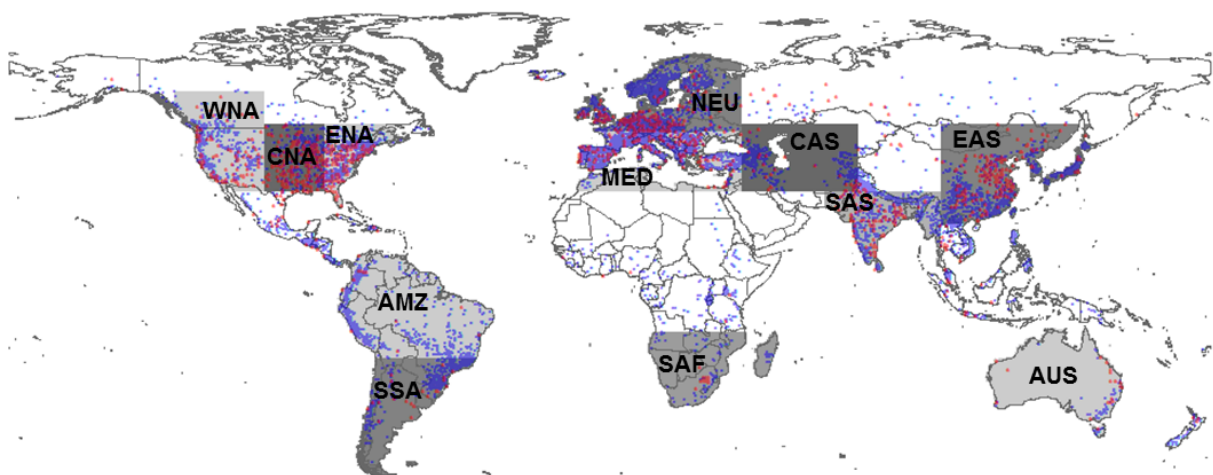141 thermoelectric power plants (n=1,321) of the plant dataset.

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144 **Figure 1.** Spatial distribution of hydropower plants (blue) and thermoelectric power plants (red) from WEPPD
145 and 12 subregions (grey-scale) for analysis of impacts of drought and warm years on hydropower and
146 thermoelectric power usable capacity. Subregions were defined by Giorgi and Francisco (2000) and adapted by
147 Sheffield and Wood (2007). Full names of selected subregions and number of hydropower plants and
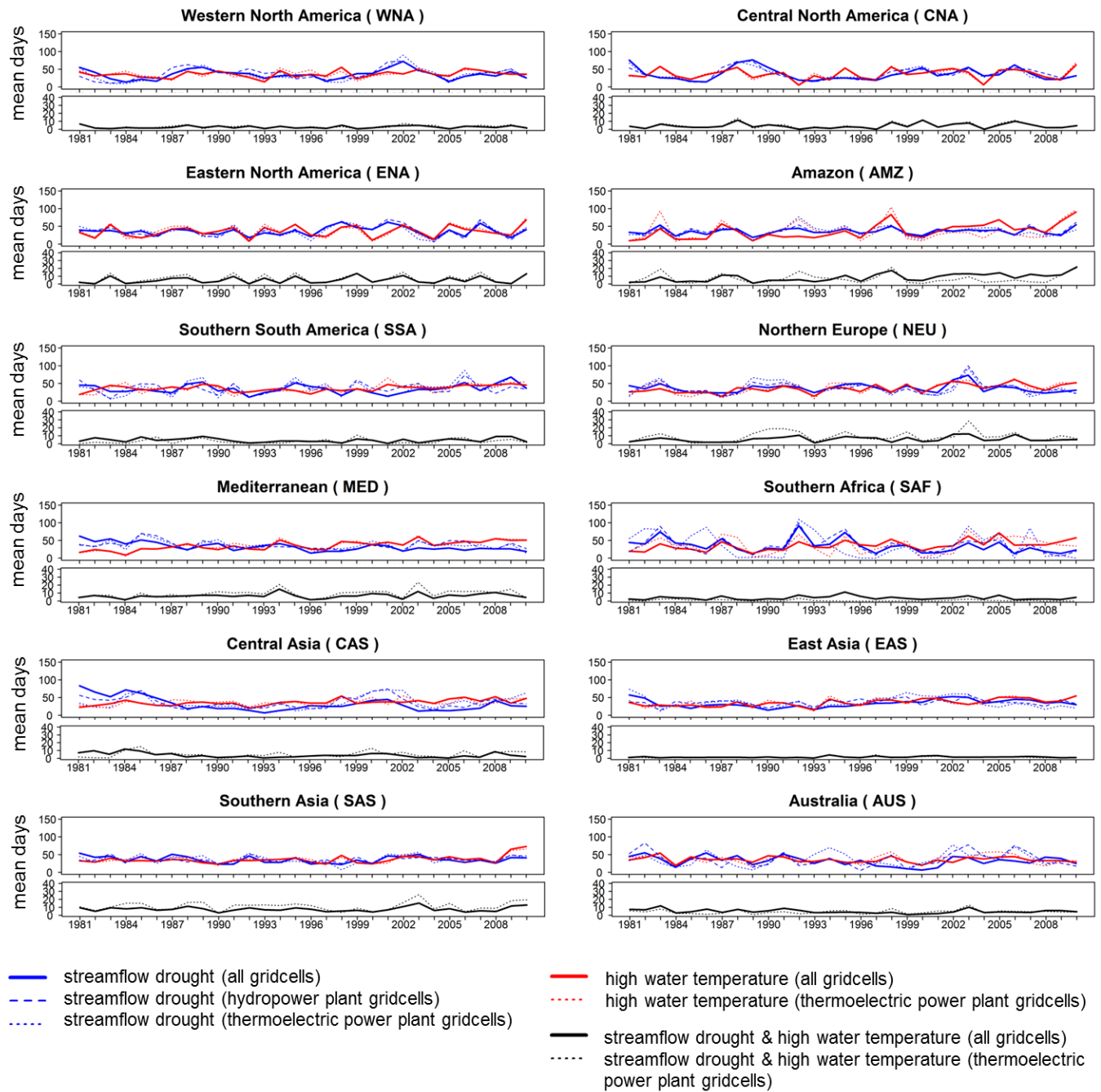148 thermoelectric plants per subregion are listed in table 1.

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150    For hydropower we identified recent critical years by selecting the three years with the highest number

151    of days with streamflow drought in each subregion. In a similar way, we identified critical years for

152    thermoelectric power by selecting the three years with highest number of days that both streamflow

153    drought and high water temperature coincided. We focused on the three most critical years to show

154    impacts of drought, warm years with an average reoccurrence of about once every ten years in each

155    subregion, and to compare impacts on this reoccurrence level between different subregions. In a next

156    step, we quantified to what extent the usable capacity of all power plants per subregion deviated

157    during these critical drought years compared to the average situation for 1981-2010. To eliminate the

158    impacts of increasing trends in usable capacity due to increases in installed capacity over 1981-2010,

159    we calculated annual average utilisation rates by dividing simulated usable capacity by installed

160    capacity of each power plant and for each year. These utilisation rates of hydropower and

161    thermoelectric power were subsequently aggregated over all power plants per subregion. Non-

162    parametric Wilcoxon rank sum tests (Wilcoxon, 1945) were then used to quantify to what extent

163    hydropower and thermoelectric power utilisation rates deviated significantly during these drought and

164    warm years compared to the average for 1981-2010. In addition, we quantified impacts of drought and

165    warm years on plants at the individual level to explore the spatial variability in response of

166    hydropower and thermoelectric power plants within the same subregion.

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169    **3. Results**

170    *3.1 Drought and high water temperature years*

171    Annual time series with the mean number of days with streamflow drought and high water

172    temperature are shown for the 12 subregions with the largest number of hydropower and

173    thermoelectric power plants (figure 2). Aggregating results over all gridcells per subregion (solids

174    lines) or only over gridcells where hydropower and thermoelectric power plants are situated (dotted,

175    dashed lines) had overall very limited impacts on the identification of the critical years with

176    streamflow drought (for hydropower) and critical years with both streamflow drought and high water

177    temperature (thermoelectric power).

178  Most severe streamflow droughts for hydropower and thermoelectric power were detected in northern

179  Europe (2003) and in southern Africa (1992) with almost 100 days of streamflow drought (i.e. values

180  lower than the 10-percentile streamflow). Most severe high water temperature years were found for

181  the Amazon region (1998, 2010) with more than 100 days of high water temperature (i.e. values

182  higher than the 90-percentile water temperature) (figure 2).



streamflow drought (all gridcells)
streamflow drought (hydropower plant gridcells)
streamflow drought (thermoelectric power plant gridcells)

high water temperature (all gridcells)
high water temperature (thermoelectric power plant gridcells)

streamflow drought & high water temperature (all gridcells)
streamflow drought & high water temperature (thermoelectric power plant gridcells)

183  **Figure 2.** Identification of streamflow drought and high water temperature years. Mean number of days per year

184  were quantified with streamflow drought (blue), high water temperature (red), and days that streamflow drought

185  and high water temperature coincide (black) for 1981-2010.

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Comparison of these time series shows that detected years with streamflow drought and high water temperature highly differ between subregions. However, some streamflow drought and high water temperature events exceed the boundaries of subregions during some critical years. This was found for example for 1988 in North America (WNA, CNA, ENA), 2003 in Europe (NEU, MED) and 2007 in the eastern United States (CNA, ENE) with large regions with streamflow drought for more than 100 days and high water temperature for more than 50 days (figure 3; left and middle panel). Boundaries of subregions were also exceeded for example for 2009 in Asia (CAS, EAS, SAS) and 2010 in South America (AMZ, SSA) with large areas of more than 100 days of high water temperature (figure 3; middle panel). Areas where streamflow drought and high water temperature coincided for more than 50 days are rather small and are mainly located in central Europe (2003), the most northern part of India (2009) and the northern part of South America (2010) (figure 3; right panel).

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Table 1 shows an overview of the three most severe streamflow drought years (for hydropower) and the three most severe years with streamflow drought and high water temperature (thermoelectric power) for each subregion for 1981-2010. While the critical years for hydropower and for thermoelectric power do not necessary coincide, we found for all subregions (except East Asia) at least one (out of the three) similar critical years for both hydropower and thermoelectric power (see years indicated in bold in table 1).
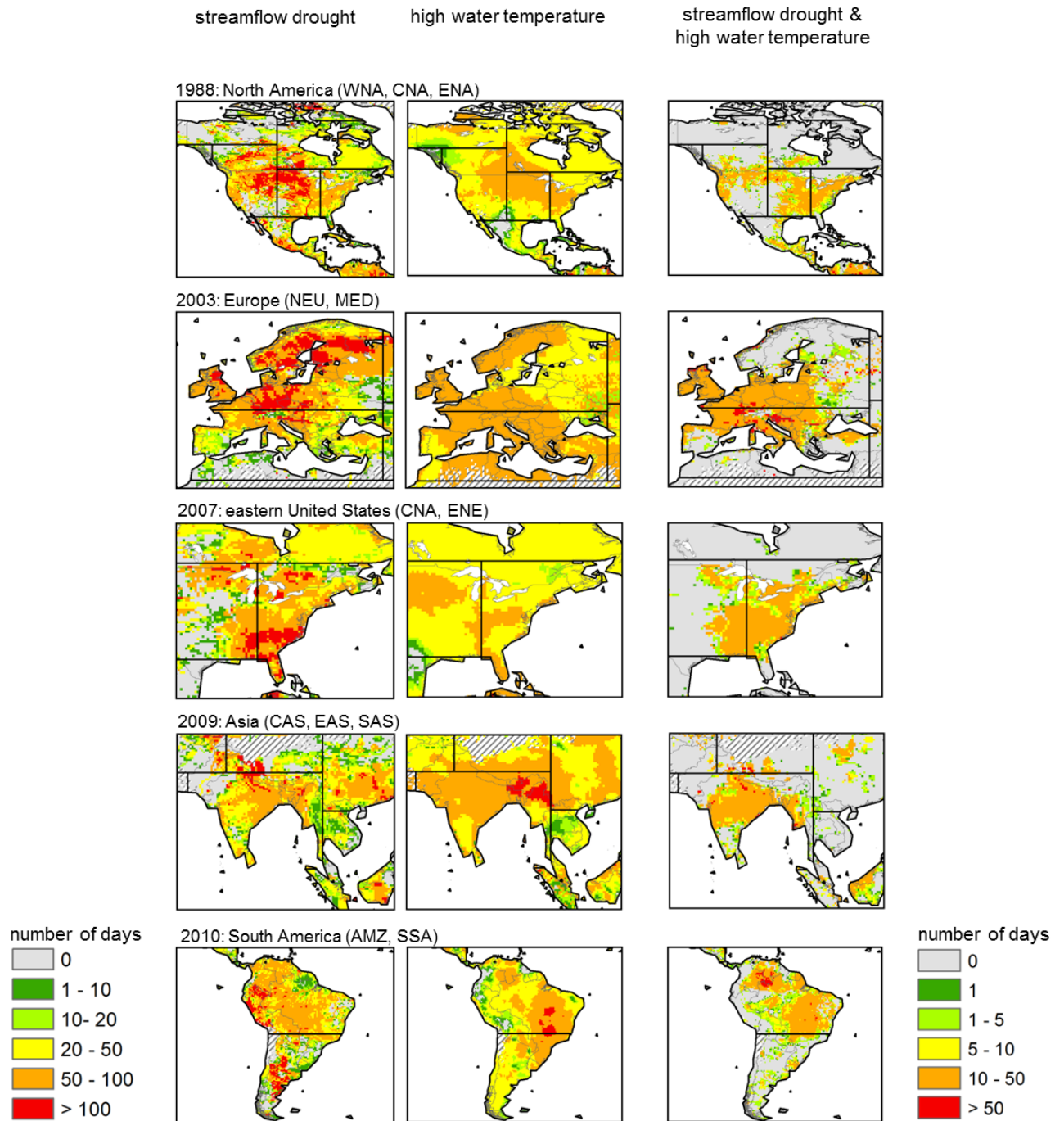
**Figure 3.** Regional patterns with number of days in the given year with streamflow drought (left), high water temperature (middle), and that both events coincide (right). Results are presented for a selection of critical years with both streamflow drought and high water temperature. Scale for right figure panels (streamflow drought & high water temperature) differs from the scale of the left (streamflow drought) and middle (high water temperature) panels.

Table 1. Overview of critical years with streamflow drought and high water temperature per subregion. Years indicated in bold are critical years for both hydropower and thermoelectric power. Years underlined indicate that usable capacity was reduced significantly (Wilcoxon Rank Sum tests; p<0.05) compared to the average over 1981-2010.

| region name | region abbre- viation | n hydro- power plants | n thermo- electric power plants | critical years hydropower | critical years thermo- electric power |
|---|---|---|---|---|---|
| **North America** | | | | | |
| Western North America | WNA | 1193 | 102 | **1988**, 2001, **2002** | <u>1981</u>, **1988**, **2002** |
| Central North America | CNA | 980 | 212 | 1987, **<u>1988</u>**, 1989 | **1988**, 2000, 2006 |
| Eastern North America | ENA | 2071 | 184 | 1998, <u>2001</u>, **2007** | 1995, 2002, **<u>2007</u>** |
| **South America** | | | | | |
| Amazon | AMZ | 1317 | 12 | 1992, 2007, **2010** | 1983, 1998, **2010** |
| Southern South America | SSA | 1078 | 19 | 1981, **1999**, <u>2006</u> | 1986, **1999, 2006** |
| **Europe** | | | | | |
| Northern Europe | NEU | 4281 | 218 | <u>1983, 1989</u>, **2003** | 1990, <u>1991</u>, **2003** |
| Mediterranean | MED | 6479 | 169 | <u>1985, 1986</u>, **2003** | 1994, **<u>2003</u>**, 2009 |
| **Africa** | | | | | |
| Southern Africa | SAF | 181 | 15 | 1982, **1992**, 1995 | 1983, 1984, **1992** |
| **Asia** | | | | | |
| Central Asia | CAS | 806 | 33 | **<u>1985, 2000</u>**, 2001 | 1984, **1985, 2000** |
| East Asia | EAS | 2255 | 217 | <u>1998, 1999, 2003</u> | 1994, <u>1997</u>, 2001 |
| Southern Asia | SAS | 1370 | 120 | <u>1983, 1992</u>, **2009** | 2003, **2009**, 2010 |
| **Australia** | | | | | |
| Australia | AUS | 130 | 20 | <u>1982</u>, **<u>2003</u>**, 2006 | 1983, 1998, **2003** |

*3.2 Impacts of drought and warm years on hydropower and thermoelectric power*

On a mean worldwide level, simulated hydropower utilisation rates were on average reduced by 5.2%, and thermoelectric power by 3.8% during the investigated drought years compared to the average for 1981-2010. These global average values were obtained by calculating the average plant utilisation rate of the three critical years compared to the long-term average utilisation rate for 1981-2010, and then averaging the results over all plants worldwide. Boxplots with the distributions of utilisation rates of all hydropower plants for the 12 subregions are shown in figure 4a. Values of 1 indicate that a power plant works at full capacity (no constraints) while for instance a value of 0.8 indicate that the plant

225  works at 80% of the maximum capacity because of water constraints. The boxplots show that in

226  Central North America, Eastern North America and Northern Europe, impacts of water constraints on

227  hydropower utilisation are lowest, while impacts in Australia and East Asia are overall largest. This is

228  related to the drier conditions and larger variability in streamflow in these regions. The interannual

229  variability in utilisation rates of hydropower is highest in Australia and Southern Africa, but this might

230  also be partly due to the low number of hydropower power plants in Australia (n=130) and Southern

231  Africa (n=181) compared to the other subregions (n>800) over which the results are aggregated. In

232  most subregions, hydropower utilisation rates were significantly reduced ($p<0.05$) for two out of the

233  three critical drought years. For Western North America, Northern Europe, Mediterranean, Central

234  Asia and East Asia, the hydropower utilisation rates were reduced significantly for all three

235  investigated drought years (table 1).

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237  Boxplots with utilisation rates of thermoelectric power are presented for the six subregions with

238  highest number of thermoelectric power plants (figure 4b). Our results show overall lower utilisation

239  rates than for hydropower, which is expected as thermoelectric power usable capacity can be

240  constrained by more factors (i.e. streamflow drought and high water temperature) and benefit less

241  from storage of water in reservoirs during the low flow conditions than conventional hydropower

242  plants. Although considerable impacts of water constraints on thermoelectric power utilisation were

243  found, these reductions were statistically insignificant ($p>0.05$) for most critical drought and warm

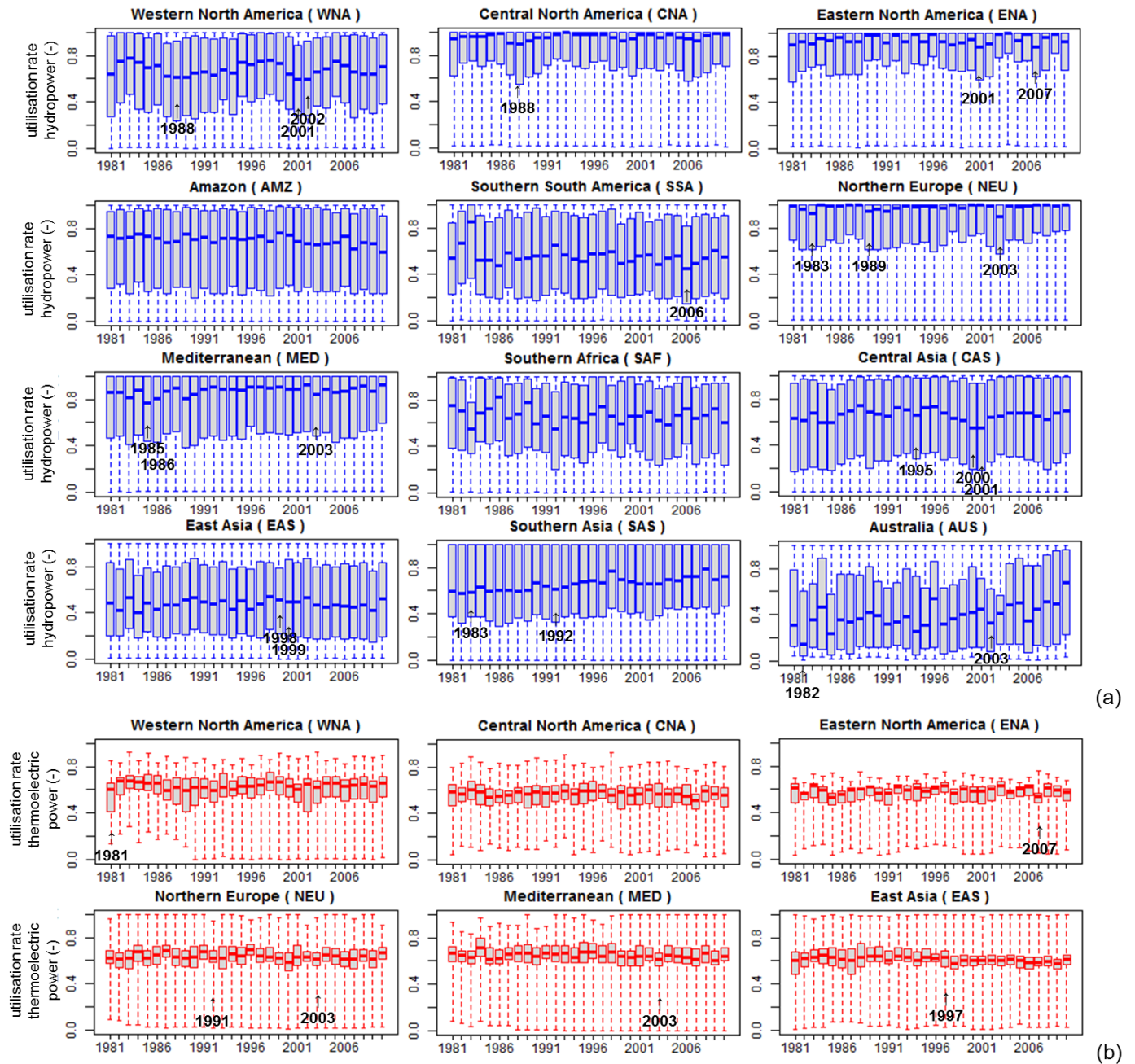244  years compared to the average of 1981-2010.

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**Figure 4.** Impacts of streamflow drought and high water temperature on utilisation rates of hydropower (a) and thermoelectric power (b) for 1981-2010. Boxplots with distributions of utilisation rates of hydropower are presented for 12 subregions and for thermoelectric power for 6 subregions with the largest number of plants and installed capacity. Highlighted years indicate that utilisation rates were reduced significantly ($p<0.05$) compared to the average over 1981-2010.

We found however strong significant ($p<0.01$) impacts on both thermoelectric power and hydropower utilisation rates during major critical years, such as 2003 in Europe (Northern Europe and Mediterranean) and 2007 in Eastern North America. During the drought year of 2003 in Europe, simulated hydropower utilisation was significantly ($p<0.01$) reduced by 6.6% and thermoelectric

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256  power by 4.7% compared to the average of 1981-2010. Although the absolute values of hydropower

257  utilisation rates are distinctly lower for the Mediterranean than for Northern Europe (figure 4), the

258  relative changes (percentage reductions) in usable capacity for 2003 compared to the long-term

259  average of 1981-2010 were larger for most hydropower power plants and thermoelectric power plants

260  in Northern Europe than in the Mediterranean region (figure 5a). This discrepancy is due to the fact

261  that power plants in the Mediterranean are hampered by water constraints on a more regular basis,

262  resulting in lower absolute values of plant utilisation rates and smaller relative changes in usable

263  capacity for 2003 compared to the long-term average for 1981-2010. For the drought year of 2007 in

264  Eastern North America significant ($p<0.01$) reductions of 6.1% in hydropower and 9.0% in

265  thermoelectric power utilisation rates were found. Largest declines were simulated for hydropower

266  and thermoelectric power plants in the state Georgia (figure 5b) where largest reductions in

267  streamflow occurred during the drought year of 2007 compared to the average of 1981-2010.
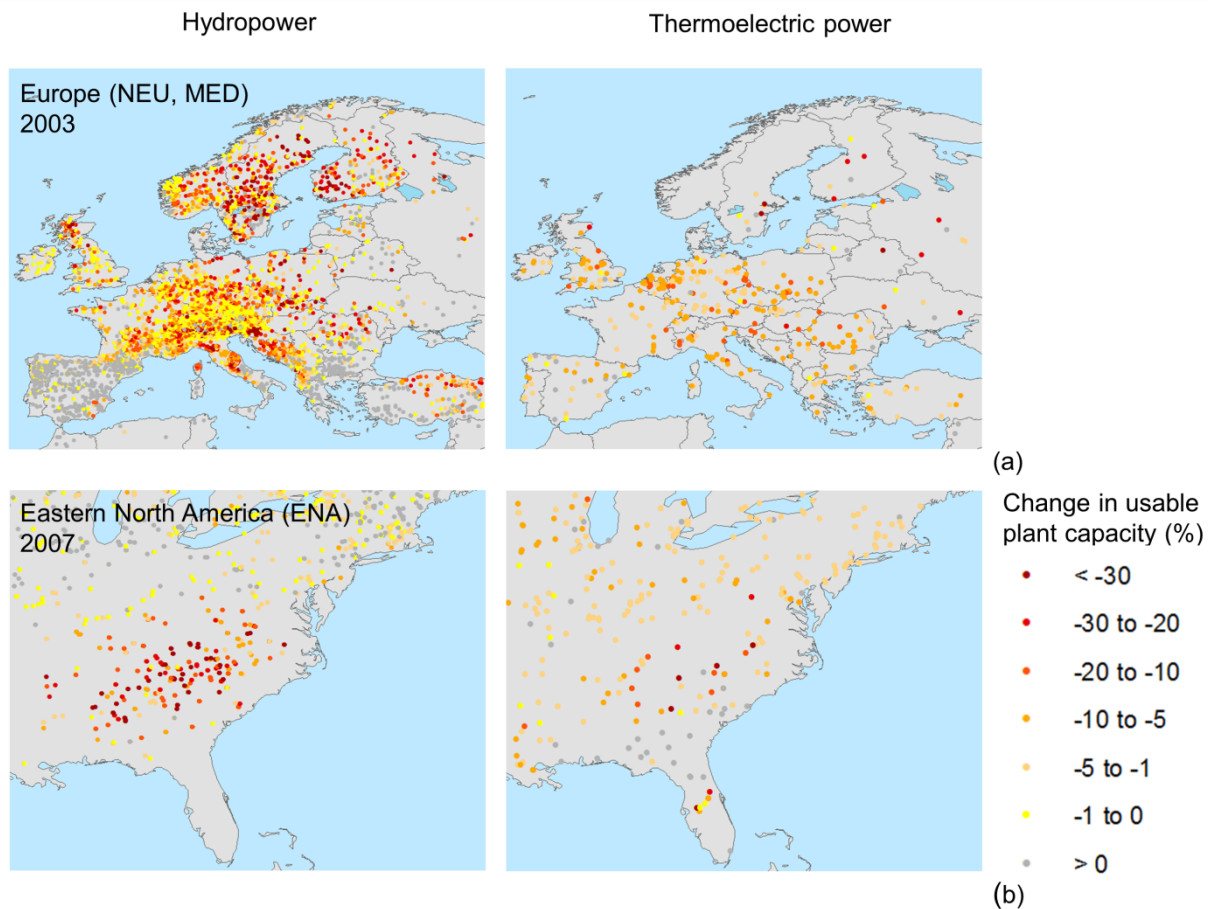
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**Figure 5.** Change in hydropower and thermoelectric power usable capacity for the drought, warm year of 2003 in Europe (a) and 2007 in the Eastern North America (b) relative to the average for 1981-2010.

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**4. Discussion and conclusions**

We identified recent years with streamflow drought and high water temperature in different subregions worldwide and studied how hydropower and thermoelectric power utilisation rates were impacted during the three most severe drought, warm years of 1981-2010 compared to the long-term average climate conditions of this 30-year period. Our results show that recent drought, warm years resulted on average in reductions of 5.2% in hydropower and 3.8% in thermoelectric power relative to the long-term average utilisation rates for 1981-2010.

A coupled hydrological-electricity modelling framework was used, which realistically represented the observed trends and interannual variability of streamflow, water temperature, hydropower and thermoelectric power generation in most regions worldwide and over long (30-year) periods (supplementary figures S1-S2 and supplementary information of van Vliet *et al.* (2016)). However, uncertainties related to the structure and parameterizations of the used models are expected to influence the assessed impacts of droughts and warm years on hydropower and thermoelectric power usable capacity. Uncertainties related to the structure and parameterization of the hydrological model and water temperature model are mainly attributed to heterogeneity in hydraulic characteristics and estimates of headwater temperatures (van Vliet *et al.*, 2012a, Yearsley, 2012). Impacts of parameters uncertainties for the hydropower model and thermoelectric power model were previously quantified for derived estimates of hydraulic head and environmental limitations on cooling water use (supplementary information of van Vliet *et al.* (2016)). In addition to the impacts of uncertainties related to the various individual models, the use of a cascade of models (VIC hydrological model – routing model – RBM water temperature model – hydropower model and thermoelectric power model) may result also in a propagation of uncertainties (e.g. Freni *et al.*, 2011, Pappenberger *et al.*, 2012). We assessed the impacts of uncertainties in simulations of streamflow and water temperature for a selection of hydropower and thermoelectric power plants by comparing usable power plant capacity based on the simulations of streamflow and water temperature with values based on observed

300  records of a nearby monitoring station for 1981-2010 (supplementary section 2.3). This showed

301  moderated impacts (i.e. relative bias in simulated usable capacity of less than 10%) for most of the

302  hydropower plants (72%) and thermoelectric power plants (78%) included in a sensitivity analysis.

303  Impacts of uncertainties (biases) in simulated water temperature were higher, although the relative bias

304  in simulated usable capacity is less than 10% for the majority (52% and 64%) of the thermoelectric

305  power plants for the 1981-2010 period and for the drought, warm years, respectively   (see

306  supplementary section 2.3).

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308  Our results show that hydropower utilisation rates were significantly reduced during the majority of

309  investigated drought years and in almost all subregions, while reductions in thermoelectric power

310  utilisation were only significant for a selection of drought, warm years compared to the average of

311  1981-2010 in some subregions (Western North America, East North America, Northern Europe,

312  Mediterranean and East Asia). This discrepancy might be explained by the fact that thermoelectric

313  power utilisation is overall constrained on a more regular basis, which results in lower absolute values

314  of utilisation rates of thermoelectric power than for hydropower (figure 4) and relatively smaller (and

315  statistically less significant) reductions during the drought, warm years compared to the average of

316  1981-2010. Thermoelectric power utilisation is hampered on a more regular basis than hydropower

317  partly because of constraints in both water availability and temperature, which directly impact cooling

318  water use potentials. In addition, there are differences in water management and institutional

319  mechanisms (e.g. reservoir operational rules, environmental regulations for cooling water uses) that

320  largely impact how hydropower and thermoelectric plants address streamflow variability.

321  Conventional hydropower plants have overall large reservoirs that act as buffers by storing potential

322  energy to help cope with hydrological variability. Although some thermoelectric power thermoelectric

323  power plants also benefit from flow regulation and water storage in reservoirs during the low flow

324  period, most thermoelectric plants withdraw water for cooling purposes from rivers where water

325  availability is not specifically optimized and regulated for thermoelectric cooling purposes (Schaeffer

326  et al., 2012). While simple operational rules are included in our hydrological-electricity modelling

327  framework, the implementation of more comprehensive water management and institutional

328    mechanisms (e.g. multi-reservoir operation and water allocation policies) (Oliveira & Loucks, 1997)

329    are recommended to better understand the impacts of droughts on hydropower and thermoelectric

330    power usable capacity informed by both the physical and anthropogenic driven constraints.

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332    Our results show that some streamflow drought and high water temperature events exceed the

333    boundaries of subregions during some critical years (figure 3). This might have important

334    implications, because when streamflow drought or high water temperature hamper hydropower and

335    thermoelectric power generation at multiple subregions at once, the potential to alleviate power

336    shortage through transmission is limited (e.g. Bartos & Chester, 2015, van Vliet *et al.*, 2013).

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338    For large-scale management of the electricity sector, especially the combination of streamflow drought

339    with high water temperature is critical, because this can hamper both hydropower and thermoelectric

340    power usable capacity with potentially drastic reductions of the reliability of the power supply system.

341    Strong significant ($p<0.01$) impacts of droughts on both hydropower and thermoelectric power

342    utilisation were found during recent major droughts years, such as 2003 in Europe (reductions of 6.6%

343    in hydropower and 4.7% in thermoelectric power) and 2007 in Eastern North America (6.1% in

344    hydropower and 9.0% in thermoelectric power) (figure 5). Both events have been characterized as

345    critical events with several power plants forced to reduce generation or shut down due to limited

346    surface water and environmental restrictions on cooling water use (e.g. Macknick *et al.*, 2011, NETL,

347    2009a, NETL, 2009b, Rübbelke & Vögele, 2011).

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349    Our hydrological-electricity modelling framework has potential for quantifying the impacts of future

350    drought and warm events under climate change and human impacts on water-dependent electricity

351    supply systems worldwide. Incorporation of the physical impacts of water constraints during drought,

352    warm years from this study into energy models describing also the economic feedbacks (e.g. supply-

353    demand portfolio) would allow a more comprehensive understanding of the impacts of drought and

354    warm events on the energy sector. The modelling framework has potential for studying how climate

355    variability and change may affect the linkages between water and energy security, contributing to the

356    quantification of the "water-energy nexus" (Stucki & Sojamo, 2012).

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