Recent progress in the understanding of changes in climate, glaciers and water resources of the upper Indus

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ICIMOD, Kathmandu, Nepal
The Indus: a thirsty basin

Dependence on glacier melt (DG)
Groundwater depletion (GD)
Reservoir potential (RP)
Future precipitation (FP)
Uncertainty in future precipitation (UP)
Economic development (ED)

Population (million)
- < 14
- 15-23
- 24-25
- 26-41
- 42-51
- 52-70
- 71-162
- 163-203
- 204-432
- 433-601

Immerzeel & Bierkens, Nature Geoscience, 2012
The Indus: an unknown climate

Immerzeel et al, HESS, 2015
The Indus: an unknown climate

Immerzeel et al, HESS, 2015
The Indus: westerlies and monsoon

Maussion et al, 2014, JoC
Observed trends

> Precipitation trends
  - Archer and Fowler, 2006, HESS:
    ▪ No long term trends (1895 – 1999)
    ▪ Statistically significant increasing trends in annual and winter precipitation between 1961-1999 for some stations
  - Palazzi, 2014, JGR:
    ▪ No statistically significant trends (~ last 50 yrs)
  - Khattak, 2011, Climate Research
    ▪ No statistically significant trends (1967 – 2005)

> Temperature trends
  - Fowler and Archer, 2005, Journal of Climate
    ▪ Increase in winter mean and maximum (1961-2000)
    ▪ Decrease in summer mean and minimum (1961-2000)
    ▪ Consistent increase in DTR in all seasons
  - Khattak, 2011, Climate Research
    ▪ Increase in winter maximum (1965 – 2005)
    ▪ Decrease in minimum temperature (1965 – 2005)
Glaciers in the upper Indus

Kääb et al, TC, 2015
## Glaciers in the upper Indus

<table>
<thead>
<tr>
<th>Zone</th>
<th>Glacier area (km²)</th>
<th>This study (m yr⁻¹, ± at 1σ-level)</th>
<th>Gardner et al. (2013; m yr⁻¹, ± at 2σ-level)</th>
<th>Neckel et al. (2014; m yr⁻¹, ± at 1σ-level)</th>
<th>Gardelle et al. (2013; m yr⁻¹, ± at 1σ-level)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eastern Nyainqêntanglhaᵃ</td>
<td>6000</td>
<td>−1.34 ± 0.29</td>
<td>−0.30 ± 0.13</td>
<td>−0.81 ± 0.32</td>
<td>−0.39 ± 0.16</td>
</tr>
<tr>
<td>Bhutan</td>
<td>3500</td>
<td>−0.89 ± 0.16</td>
<td>−0.89 ± 0.18</td>
<td>−0.78 ± 0.27</td>
<td>−0.26 ± 0.15</td>
</tr>
<tr>
<td>Everest</td>
<td>8500</td>
<td>−0.37 ± 0.10</td>
<td>−0.44 ± 0.20</td>
<td></td>
<td>−0.30 ± 0.16</td>
</tr>
<tr>
<td>West Nepal</td>
<td>7500</td>
<td>−0.43 ± 0.09</td>
<td>−0.44 ± 0.26</td>
<td>−0.38 ± 0.16</td>
<td></td>
</tr>
<tr>
<td>Spiti–Lahaul</td>
<td>9500</td>
<td>−0.49 ± 0.12</td>
<td>−0.53 ± 0.13</td>
<td>−0.53 ± 0.16</td>
<td></td>
</tr>
<tr>
<td>Karakoram</td>
<td>21 000</td>
<td>−0.10 ± 0.06</td>
<td>−0.12 ± 0.15</td>
<td>+0.12 ± 0.19</td>
<td></td>
</tr>
<tr>
<td>Hindu Kush</td>
<td>5500</td>
<td>−0.49 ± 0.10</td>
<td>−0.13 ± 0.22</td>
<td>−0.14 ± 0.19</td>
<td>+0.16 ± 0.15</td>
</tr>
<tr>
<td>Pamir</td>
<td>6500</td>
<td>−0.48 ± 0.14</td>
<td></td>
<td></td>
<td>+0.16 ± 0.15</td>
</tr>
<tr>
<td>Western Kunlun Shan–Tarim</td>
<td>12 500</td>
<td>+0.05 ± 0.07</td>
<td>+0.17 ± 0.15</td>
<td>+0.04 ± 0.29</td>
<td></td>
</tr>
<tr>
<td>Area-weighted mean</td>
<td>80 500</td>
<td>−0.37 ± 0.10</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

ᵃ Kääb et al., TC, 2015
Glacier surges in the upper Indus
Glaciers in the upper Indus

<table>
<thead>
<tr>
<th>Major river basin</th>
<th>Glacier area (km²)</th>
<th>Elevation difference trend (m yr⁻¹)</th>
<th>Mass change (Gt yr⁻¹)</th>
<th>Discharge equivalent DE (m³ s⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tarim</td>
<td>15 000</td>
<td>+0.06 ± 0.08</td>
<td>+0.7 ± 1.0</td>
<td>+24 ± 33</td>
</tr>
<tr>
<td>Amu Darya</td>
<td>11 000</td>
<td>−0.43 ± 0.08</td>
<td>−4.0 ± 0.8</td>
<td>−128 ± 25</td>
</tr>
<tr>
<td>Indus</td>
<td>25 000</td>
<td>−0.33 ± 0.04</td>
<td>−7.0 ± 0.8</td>
<td>−220 ± 26</td>
</tr>
<tr>
<td>Ganges</td>
<td>11 000</td>
<td>−0.44 ± 0.07</td>
<td>−4.1 ± 0.6</td>
<td>−130 ± 20</td>
</tr>
<tr>
<td>Brahmaputra</td>
<td>14 000</td>
<td>−1.06 ± 0.15</td>
<td>−12.6 ± 1.9</td>
<td>−400 ± 60</td>
</tr>
</tbody>
</table>

Kääb et al, TC, 2015
Flow composition

Glacier

Snow

Rain

Lutz et al, 2016, PlosOne (under review)
Climate change scenarios

Immerzeel et al., 2013, Nature geoscience
Future hydrology

Immerzeel et al., 2013, Nature geoscience
Future hydrology

Lutz et al., 2016, PlosOne (under review)
Future challenges

> Reconciling the observed trends in temperature, precipitation and streamflow with the overall glacier mass loss

> Understanding of the Karakoram anomaly
  - Where is it located?
  - What is the relation with the surge type glaciers?
  - What are the underlying mechanisms for the anomaly?

> Feedbacks between cryosphere – atmosphere - hydrosphere

> Bridging the scale gap between climate models, hydrological models and scarce observations

> Quantification of changes in extremes
THANK YOU!