Contributions of BALTEX towards the understanding of the Earth’s water and energy cycle

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BALTEX and the global water and energy cycle

• The global water cycle and its fundamental importance

• What have we learned from BALTEX?

• Response of the global water cycle to temperature

• What might happen to higher latitudes in a warmer climate?

• Concluding remarks
Global water reservoir and fluxes
(Baumgartner & Reichel; 1975)

Atmosphere
13

Evaporation Transpiration
2.2 Sv

Precipitation
3.5 Sv

Evaporation
13.5 Sv

Precipitation
12.2 Sv

LAND
59,000

Rivers
1.3 Sv

OCEAN
1,400,000

Reservoir in $10^3$ km$^3$, Fluxes in $10^6$ m$^3$/s (=Sv)*

(* Sv = $10^6$ m$^3$/s = 31.5 • $10^3$ km$^3$/year)
The radiation budget of the Earth

\[ E_{\text{in}} = E_{\text{out}} \iff \frac{1}{4} S_0 (1 - \alpha) = \varepsilon \sigma T_s^4 \]

Annual global energy flows W m\(^{-2}\) Latent heat is ca 25% of the solar constant
Surface water balance, mm/day

Evaporation minus precipitation

1 mm/day = 29 W/m²

Annual mean

Borgholm 11 June 2013

BALTEX water cycle
The global water cycle

Figure 1. The global water cycle following Baumgartner and Reichel (1975). Annual values are in units of $10^3$ km$^3$ year$^{-1}$. 
Supply of water from the oceans

[36 \times 10^3 \text{ km}^3 / \text{year}]

0.8%  32%  31%  34%
Return of water to the oceans

[34 \times 10^3 \text{ km}^3 / \text{year}]
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Precipitation over land: GPCP: 1365 mm. Rubel and Hantel 2001): 1307 mm

Net outflow close to various estimates Omstedt and Rutgersson (2000)

1 km$^3$/year = 31.7 m$^3$/sec
# Extreme precipitation in Uppsala 1722-2007

<table>
<thead>
<tr>
<th>Wettest year:</th>
<th>1866</th>
<th>812 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wettest month:</td>
<td>July 1898</td>
<td>200 mm</td>
</tr>
<tr>
<td>Wettest day:</td>
<td>17 Aug 1997</td>
<td>104 mm</td>
</tr>
<tr>
<td>Driest year:</td>
<td>1875</td>
<td>311 mm</td>
</tr>
<tr>
<td>Driest month:</td>
<td>March 1964</td>
<td>0.2 mm</td>
</tr>
</tbody>
</table>

Credit: Hans Bergström, Uppsala University
Annual precipitation for Sweden 1860-2011
Credit: SMHI

A minor increase is indicated, some 50-75 mm
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Clausius-Clapeyron relation

Relation between temperature, $T$ and saturated water vapor, $e_s$

$$\frac{d \ln e_s}{dT} = \frac{L}{RT^2} \equiv \alpha(T),$$

Atmospheric temperature determines water vapour following the C-C relation
Water vapour and temperature

For a temperature change, \( dT \), the humidity change, \( dq \), follows the C-C relation seen as a conservation of relative humidity

\[
dT + 0.4^\circ C
dq + 3\%
\]

Model 1860-2100

\( dT + 4^\circ C \)
\( dq + 35\% \)

Observations and model calculations from observed SST 1979-2005

Held and Soden, 2006

Semenov and Bengtsson, 2002

Borgholm 11 June 2013

BALTEX water cycle
Horizontal transport of moisture, $F$

- After Held and Soden (2006)

- Horizontal transport of moisture from the IPCC scenario A1B (solid)

- Transport by the simple formula (2) scaled by CC (dashed)

\[
\frac{\delta F}{F} \approx \frac{\delta e_s}{e_s} \approx \alpha \delta T. \tag{2}
\]
Effect on P-E

The result for precipitation minus evaporation is

$$\delta(P - E) = -\nabla \cdot (\alpha \delta TF). \quad (5)$$

If one can remove $\delta T$ from the derivative, assuming that $P - E$ has more meridional structure than $\delta T$, then $P - E$ itself satisfies CC scaling:

$$\delta(P - E) = \alpha \delta T(P - E). \quad (6)$$
Change of the hydrological cycle

IPCC 4th assessment, 2007

a) Precipitation
b) Soil moisture
c) Runoff
d) Evaporation
The atmospheric water cycle

• The atmospheric water cycle follows closely Clausius-Clapeyrons (C-C) relation. (6-7%/ K)

• It also follows that transport of water vapour scales with the C-C relation.

• That means more precipitation in areas of convergence

• The global precipitation increases much slower than global water vapor. (1-2%/ K)
Fig. 3. Hourly model diagnostic results for the ‘virtual’ forcing of climate by instantaneous water vapor changes. There is rapid convergence to equilibrium following instantaneous doubling and zeroing of atmospheric water vapor. The left-hand panels show global-mean water vapor at 299 and 974 mb level converging to control run equilibrium values. The right-hand panels show the up-welling LW flux at the top (TOA) and the bottom (BOA) of the atmosphere. Diurnal oscillations in the global-mean LW flux arise from the diurnal surface temperature change over land areas. Red curves depict the model response to doubled water vapor amounts. The green curves refer to the model response to zeroed water vapor. The blue curves are for the control run water vapor reference results. Water vapor changes in the left-hand panels have been normalized relative to the control run results.
CO\textsubscript{2} is a genuine forcing, while H\textsubscript{2}O is a part of the climate response system

- The residence time of CO\textsubscript{2} in the atmosphere is from years to multi-millennia
- The residence time of H\textsubscript{2}O in the atmosphere is 7-8 days
- H\textsubscript{2}O, albeit a more powerful greenhouse gas, is driven by temperature that in turn is forced by the slower components of the climate system.
Why is water vapour increasing faster than precipitation in global mean and what is the reason?

- Water vapour is controlled by the 3-dimensional atmospheric circulation.

- Precipitation = Evaporation is determined by the surface energy balance.

- While water vapour always will increase in a warmer climate, global precipitation can under certain conditions, such as enhanced aerosol load, even decrease!
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Climate change experiment using ECHAM5
Bengtsson et al., 2011 (Tellus)

- We have investigated two periods:
  - 20 C: 1959-1990 using observed/estimated greenhouse gases and aerosols
  - 21 C: 2069-2100 using scenario A1B

- A1B is a middle-of-the-line scenario

- Carbon emission peaking in the 2050s (16 Gt/year)
  - CO$_2$ reaching 450 ppm. in 2030
  - CO$_2$ reaching 700 ppm. in 2100

- SO$_2$ peaking in 2020 then coming done to 20% thereof in 2100
Transport of water vapour across 60° N

Annual mean calculated for every 6 hrs. T213 resolution (ca 50 km)

ERA-Interim re-analysis
1989-2009 (Observation)

ECHAM5 (T213) for the period
1959-1990 (Modellberäkning av nuvärden)

ECHAM5 (IPCC scenario A1B)
2069-2100 (Modellberäkning av den framtidiga värdet)

Bengtsson et al., 2011
High latitude energy balance end 20C and at the end of 21C

*Bengtsson et al. 2013 J. of Climate*

Units Watt/m² T63(T213)

Across 60° N and 60° S

<table>
<thead>
<tr>
<th></th>
<th>Lq</th>
<th>$C_pT+gZ$</th>
<th>$F_{Wall}$</th>
<th>$F_{SFC}$</th>
<th>$F_{RAD}$</th>
<th>$dE/dt$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>NH</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20C</td>
<td>21.7(20.9)</td>
<td>68.5(64.6)</td>
<td>90.2(85.5)</td>
<td>13.4(11.5)</td>
<td>-102.9(-98.7)</td>
<td>0.7(-1.7)</td>
</tr>
<tr>
<td>21C</td>
<td>27.3(27.0)</td>
<td>65.0(58.9)</td>
<td>92.3(85.9)</td>
<td>11.5(9.1)</td>
<td>-103.0(-99.3)</td>
<td>0.8(-4.3)</td>
</tr>
<tr>
<td>21C-20C</td>
<td>5.6 ( 6.1)</td>
<td>-3.5(-5.7)</td>
<td>2.1( 0.4)</td>
<td>-1.9(-2.4)</td>
<td>-0.1(-0.6)</td>
<td>0.1(-2.6)</td>
</tr>
<tr>
<td><strong>SH</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20C</td>
<td>26.0(28.0)</td>
<td>61.8(56.3)</td>
<td>87.8(84.3)</td>
<td>9.7( 8.0)</td>
<td>-95.6(-92.2)</td>
<td>1.9(-1.1)</td>
</tr>
<tr>
<td>21C</td>
<td>32.1(34.0)</td>
<td>53.2(47.7)</td>
<td>85.3(81.8)</td>
<td>6.1( 4.2)</td>
<td>-92.3(-89.7)</td>
<td>-0.9(-3.7)</td>
</tr>
<tr>
<td>21C-20C</td>
<td>6.1 ( 6.0)</td>
<td>-8.6(-8.6)</td>
<td>-2.5(-2.5)</td>
<td>-3.6(-3.8)</td>
<td>3.3( 2.5)</td>
<td>-2.8(-2.6)</td>
</tr>
</tbody>
</table>

Lq: **wet energy**, $C_pT+gZ$: **dry energy**, $F_{Wall}$: **net polar transport**, $F_{SFC}$: **surface transport**, Frad: **outgoing radiation**
Massbalance changes over 100 years
GREENLAND

Bengtsson et al., 2011
Surv. Geophys.

- 519 km$^3$/year
Mass balance changes over 100 years
ANTARCTICA

+289 km³/year
Sea level changes due to mass balance changes on the land ices. Contribution from Greenland (red), from Antarctica (blue). Total contribution (black).

ECHAM5 model, IPCC Scenario A1B, Credit: MPI, Hamburg
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Conclusions

• BALTEX has been very useful for model development

• There are certainly indications of fine scale deficiencies

• Larger scale features seem to be quite realistic

• While we have good reasons to be critical to models we should not have any over belief in observations

• We have reasons to expect significant changes in the water cycle at a warmer climate but it is probably not possible to identify this at present. The natural variability is generally strongly underestimated

• The poor greenhouse gases are blamed for everything in the weather. In some connections any proofs are not needed any longer.
Thanks for your attention!
20th and 21st century ice-volume changes from 'IPCC-style' pattern scaling

Surface mass balance changes only
Temperature and precipitation forcing from available AOGCMS

IPCC AR4 sea level change 21st century:
-2 to -14 cm from SMB

To counter this by ice dynamics requires sustained speedup of *all* outlet glaciers by 5-30%!
(or: 25-150% of WAIS only glaciers)


20th century rate: \(-0.153 \pm 0.123\) mm/yr
21st century rate: \(-0.865 \pm 0.400\) mm/yr
or \(-8.7\) cm/century s.l

Antarctic ice sheet SMB slightly increases
Model results and observations so far.
Credit: J Christy
What is happening to the hydrological cycle?  
The global precipitation during 100 years