EDITORIAL

The global atmospheric water cycle

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Water vapour plays a key role in the Earth’s energy balance. Almost 50% of the absorbed solar radiation at the surface is used to cool the surface, through evaporation, and warm the atmosphere, through release of latent heat. Latent heat is the single largest factor in warming the atmosphere and in transporting heat from low to high latitudes. Water vapour is also the dominant greenhouse gas and contributes to a warming of the climate system by some 24°C (Kondratev 1972). However, water vapour is a passive component in the troposphere as it is uniquely determined by temperature and should therefore be seen as a part of the climate feedback system.

In this short overview, we will first describe the water on planet Earth and the role of the hydrological cycle: the way water vapour is transported between oceans and continents and the return of water via rivers to the oceans. Generally water vapour is well observed and analysed; however, there are considerable obstacles to observing precipitation, in particular over the oceans. The response of the hydrological cycle to global warming is far reaching. Because different physical processes control the change in water vapour and evaporation/precipitation, this leads to a more extreme distribution of precipitation making, in general, wet areas wetter and dry areas dryer. Another consequence is a transition towards more intense precipitation. It is to be expected that the changes in the hydrological cycle as a consequence of climate warming may be more severe than the temperature changes.

Water on planet Earth

The total amount of available water on the Earth amounts to some $1.5 \times 10^9$ km$^3$. The dominant part of this, $1.4 \times 10^9$ km$^3$, resides in the oceans. About $29 \times 10^6$ km$^3$ are locked up in land ice and glaciers and some $15 \times 10^6$ km$^3$ are estimated to exist as groundwater. If all land ice and glaciers were to melt the sea level would rise some 80 m (Baumgartner and Reichel 1975).

$13 \times 10^3$ km$^3$ of water vapour are found in the atmosphere corresponding to a global average of 26 kg m$^{-2}$ or 26 mm m$^{-2}$ of water for each column of air on the surface of the Earth. There are large geographical differences such as between low and high latitudes. Figure 1 shows an estimate of the global water exchange between ocean and land, an annual average in units of $10^3$ km$^3$ (Baumgartner and Reichel 1975). An updated version can be found in Trenberth et al 2007 (their figure 1) showing broadly similar results.

There is a net transport of some 38 units from ocean to land with about the same amount returning by the rivers to the ocean. However the amount of precipitation over the continents is almost three times as high, indicating a considerable recirculation of water over land. As shown by Trenberth et al (2007) the recirculation has a marked annual cycle as well as having large variations between continents. The recirculation is larger during the summer and for tropical land areas.

The hydrological cycle of the world’s oceans interacts differently with that of the continents. Most of the water from the Pacific Ocean recirculates between different parts of the Pacific itself, as and there is little net transport towards land. The pattern of water exchange between ocean and land is different in the Atlantic and Indian Oceans. Two thirds of the total net transport of water towards the continents comes from the Atlantic Ocean, with the rest essentially from the
Indian Ocean. Most of the continental water for North and South America, Europe and Africa emanates from the Atlantic and is also returned to the Atlantic by the rivers.

There is widespread evaporation (maximum some 2 m year\(^{-1}\)) on each side of the inter-tropical convergence zone (ITCZ), transporting water vapour into the ITCZ and into the storm tracks of high latitudes. Conversely, in regions of net evaporation ocean salinity is increasing, leading to increased ocean vertical mixing. In the ITCZ and in the extra-tropical storm tracks ocean salinity is decreasing due to high precipitation thus reducing ocean vertical mixing. This means that moisture convergence in the atmosphere is compensated for by moisture divergence (salinity convergence) and vice versa in the oceans, which can be seen as a counterpart to the atmospheric circulation (Webster 1994).

Atmospheric water vapour is measured both from space and from \textit{in situ} observations and analysed in detail both by the operational weather services and through different re-analysis programs (e.g. Uppala \textit{et al} 2005, Onogi \textit{et al} 2007). However, while data for atmospheric water vapour are generally well observed we are much less comfortable with observations of precipitation. Precipitation has a large variance on small time and space scales and current observing systems cannot sample this sufficiently. This is especially the case over ocean areas where measurements from ships are notoriously poor as the collection of precipitation is strongly influenced by wind, including the local wind effect caused by the movements of the ship itself. Different proxy methods have been developed using space and rain gauge data and combining these with model data. The most commonly used are the NOAA Climate Prediction Centre Merged Analysis of Precipitation (CMAP; Xie and Arkin 1997) and the Global Precipitation Climatology Project (GPCP; Adler \textit{et al} 2003). GPCP consists of combined satellite and \textit{in situ} precipitation measurements and provides global coverage of monthly averages. As with most climate data sets, great caution should be exercised in trying to identify trends in precipitation (e.g. Allan and Soden 2007). In addition to the severe sampling problems we also have to identify the effect caused by ongoing changes in the global observing systems.

Hagemann \textit{et al} (2006) has undertaken a study using the ECHAM5 model (Roeckner \textit{et al} 2003, 2006) where they compared the hydrological cycle over 20 years using 11 different model versions having resolutions from T21/L19 (spectral...
transform model until wave number 21 and with 19 vertical levels) to T156/L31. There is a minor increase in global precipitation with resolution by some 7% (between T21/L19 and T156/L31) with a systematic increase of large-scale precipitation and reduced convective precipitation with resolution. There is generally good agreement between model results and CMAP and GPCP over land but the modelled precipitation is larger over the oceans by some $70 \times 10^3$ km$^3$ year$^{-1}$ on average. Whether this implies that the model overestimates precipitation over oceans cannot be concluded as it might equally well imply that the CMAP and GPCP underestimate. Another way of evaluating the hydrological cycle is to measure the river outflow and compare this with the net water flux of the river catchments. A detailed study has been conducted for the different sub-regions of the Baltic Sea covering some 10 years with excellent agreement between observed river outflow and calculations of the atmospheric water cycle from a limited area model (figure 2; D Jacob 2001, private communication). This suggests that, when reliable river outflow data exist, this is an alternative way to validate the model-generated atmospheric hydrological cycle for a larger scale area.

**Figure 2.** Model simulation of the water balance of the Baltic Sea (1979–1988). Units in km$^3$ year$^{-1}$. (Courtesy D Jacob (2001) Max-Planck-Institute for Meteorology, Hamburg.) The estimated total river run off agrees broadly with measured data (Raschke et al (2001)). The net outflow from the Baltic Sea is close to various estimates (e.g. Omstedt and Rutgersson 2000). Net water vapour inflow into the region is calculated under the assumption of long-term water balance.
Water vapour as a greenhouse gas

Water vapour is the dominant greenhouse gas and accounts for around 75% of the total greenhouse effect on Earth (Kondratev 1972). Water vapour in the atmosphere is strongly controlled by the atmospheric circulation. If, for example, we follow a trajectory of water vapour in the atmosphere it shows that it undergoes a complex series of vertical and horizontal motions that can include several events of condensation. At any given time the saturation mixing ratio is determined by the temperature of the latest event of condensation. For this reason it follows that the mixing ratio will increase with temperature broadly following the Clausius–Clapeyron relation (Pierrehumbert et al 2007).

The residence time of water vapour in the atmosphere is about a week, as compared with the very long residence time of the greenhouse gases, in particular CO$_2$ which includes multi-centennial time scales. Water vapour is, of course, continuously replenished by evaporation from the oceans and the land surfaces but is nevertheless regulated by temperature.

In that sense, water vapour should be seen as a part of the response of the climate system to external forcing. Such a change in climate forcing can be due to changes in the concentration of the more persistent greenhouse gases such as CO$_2$. Alternatively it can be due to changes in solar radiation, or to aerosols from volcanic eruptions or due to anthropogenic emissions.

The absorption bands in the water vapour spectra are close to saturation, similar to those of CO$_2$, with the absorption mainly occurring in the wings of the spectral bands. The total effect on the radiation balance can be approximated by a logarithmic function of the mixing ratio. This is how the effect of atmospheric water vapour is included in the code for the calculation of long-wave radiation in weather and climate models.

In contrast to the well-mixed greenhouse gases, water vapour varies strongly in the atmosphere and this on a small scale in both time and space. The reason is strong vertical motion of different signs that implies sharp gradients in the moisture field. Climate models that have coarse resolution have difficulties in representing sharp gradients and generally underestimate the strong outgoing long-wave radiation (OLR) in dry air. Because of the logarithmic function of the mixing ratio this implies an underestimation of OLR. Hagemann et al (2006) noted a decrease of OLR in clear sky by 7 W m$^{-2}$ by reducing the horizontal spectral resolution from T159 to T21. Furthermore a correct vertical distribution of water vapour is essential as water vapour in the upper troposphere is proportionately more important.

All indications are that water vapour constitutes a positive feedback but the strength of the feedback is debated. Observational as well as modelling studies (Held and Soden 2006, Semenov and Bengtsson 2002) suggest that the relative humidity is broadly maintained and water vapour closely follows the Clausius–Clapeyron relation. The feedback effect cannot be determined from observational studies but can be estimated from models through bypassing the part of the long-wave radiation code that calculates the effect of increasing water vapour (Hall and Manabe 1999). They showed that water vapour increases the effect of a doubling of the CO$_2$ concentration from 1.05°C to 3.38°C, suggesting a clear positive feedback from water vapour. However, a more recent analysis by Soden and Held (2006) give an amplification factor of 1.9 to 3.2 by water vapour alone, yet much of this spread is due to different changes in lapse rate; when water vapour and lapse rate are considered together the amplification of warming by these feedbacks is around 1.3 to 1.6 (Randell et al 2007, figure 8.14 and footnote).

How will precipitation change in a warmer climate?

Observational studies, as well as numerical models, show that water vapour in the atmosphere closely follows temperature in agreement with the Clausius–Clapeyron relation. That means that an increase in temperature by 1°C...
in the lower troposphere implies an increase in the vertical profile of water vapour by 6–7%. However, the increase in the hydrological cycle (global mean precipitation and evaporation) as obtained from model integration is limited to some 1–2% (Held and Soden 2006). This is because atmospheric water vapour is determined from atmospheric circulation in a warmer climate while global precipitation is constrained by evaporation from the surface. This in turn is a consequence of the radiation imbalance at the surface as well as being influenced by surface winds, stability of the boundary layer and the absorption of short-wave radiation in the atmosphere.

According to Takahashi (2009) the change of the sum of latent heat flux and short-wave absorption at the surface by temperature is broadly controlled by the long-wave flux above the boundary layer that is well understood and modelled. It may therefore be considered unlikely that models can be wrong by factors of several 100%. Rather it is more likely that models might even overestimate the latent heat flux due to an underestimation of the absorption of short-wave radiation in the atmosphere as line-by-line integration suggests a larger absorption by water vapour than what is used in climate models (Takahashi 2009).

The fact that water vapour is increasing faster than precipitation has far-reaching consequences (Held and Soden 2006). Because the increase in the strength of the global atmospheric hydrological cycle is constrained by small changes in latent heat flux (Richter and Xie 2008), it cannot keep up with the rapid increase in atmospheric water vapour. This implies that the residence time of water vapour in the atmosphere is increasing; that means that the exchange of mass between the boundary layer must decrease and, since much of this exchange occurs in moist convection in the Tropics, the convective mass flux must consequently decrease. This result is perhaps counterintuitive to some of the ideas that flourish in the climate change debate where it is implicitly assumed that the atmosphere will in some sense become more energetic as it warms. But, in fact, the average vertical exchange of mass between the boundary layer and the free atmosphere must imply a slowing down of the large-scale atmospheric circulation. To what extent this will affect tropical cyclones is not clear but it has been suggested (Bengtsson et al. 2007) that this could be the reason for the reduced number of tropical cyclones in a warmer climate.

The fact that the increase in water vapour follows the Clausius–Clapeyron relation has a number of other important consequences including the poleward transport of water vapour and the pattern of evaporation–precipitation (E–P). The (E–P) gradient increases proportionally to the lower tropospheric water vapour (Held and Soden 2006), implying that wet regions get wetter and dry regions drier. This result is of key importance for understanding how future patterns of precipitation might change in a warmer climate. This includes more precipitation in the ITCZ and in the middle- and high-latitude storm tracks and alternatively less precipitation in mid-latitudes including the Mediterranean region, California and Texas, southern Africa and southern Australia.

Changes in extreme precipitation

The distribution of precipitation as a function of time is mostly represented by a gamma function, since a comparatively large part of the total precipitation at a given place occurs during short time intervals (Juras 1994). The reason is that in most precipitation situations small-scale convective systems develop with large vertical motions that generate intense precipitation. As described by Bengtsson (2001 and references therein), convective processes are embedded in practically all precipitation systems including warm front conditions at high latitudes during the cold season. Intense precipitation dominates, in particular, convectively driven storms such as tropical cyclones. It is during such events that enormous amounts of precipitation have been measured including cases with some 1000 mm precipitation or more in less than 12 hours (http://en.wikipedia.org/wiki/List_of_weather_records#Rain). The most severe damages to society are
related to intense precipitation occurring on time scales from hours to a couple of days. A most important question is, consequently: what may happen to intense precipitation in a warmer climate?

Model experiments (Bengtsson et al 2009) for a warmer climate show a marked increase in extreme precipitation. In the storm track region there are increases in extreme 6 hr precipitation of 40–50% (at the 99 percentile or higher). As there is a much smaller increase in the average precipitation, this means that the whole spectrum of precipitation changes (Semenov and Bengtsson 2002). As the climate warming so far has been rather modest and only about some 25% compared to the experiment used by Bengtsson et al (2009), we expect it will be difficult to observe such changes in the time spectrum of precipitation. However, there are some signals from natural variability, e.g. Allan and Soden (2008). Furthermore, this will require persistent high-quality observations over a very long period of time. Karl and Knight (1998) have examined the precipitation at the 90th percentile or higher for an area over central USA and noted an increase that was found to broadly agree with the modelling result by Semenov and Bengtsson (2002, their figure 4(a)).

The large increase in extreme precipitation suggested from models is likely to have serious consequences. The change in the time distribution of precipitation intensity will radically reduce the probability of the return of extreme events. Using the same model experiment as the one by Semenov and Bengtsson it was found that the 50-year return flow in the Yangtse river calculated from model results representative for the present climate was changed to a 5 year return flow for a climate that might be expected at the end of this century using the IPCC A1B (moderate) scenario (Voss et al 2002). If such changes occur the consequences will be severe, requiring urgent enhancements of flood protection systems.

Tropical cyclones are driven by organized convection that in turn will become more intensive as the amount of available water vapour is increasing in a warmer climate. This has been found to occur but will require a high horizontal resolution (Bengtsson et al 2007, Oouchi et al 2006). Bengtsson et al (2007) found when using a global model at T319 resolution (around 40 km grid distance) that intense storms of category 3 or higher increased from 12 to 17 year\(^{-1}\) overall for the Northern Hemisphere, while the total number of tropical cyclones decreased. Similar results were obtained by Oouchi et al (2006) and Binder et al (2010) in a recent study of Atlantic hurricanes. Binder et al used a two-step downscaling of individual storms to better describe the detailed hurricane structure. So in general it seems that the large increase in water vapour in a warmer climate might not only change the structure of precipitation events but also the statistical distribution of weather systems driven by release of latent heat in a similar way. This is very important, as damages are broadly proportional to the third power of the wind speed.

Discussion

Water vapour is of fundamental importance for the climate system. The transport of water from the surface of the Earth cools the surface and warms the atmosphere with an average of around 80 W m\(^{-2}\). Water vapour flux is a key mechanism in transporting energy between low and high latitudes. The atmospheric water cycle is important for the ocean circulation. In areas of net evaporation, salinity is increasing resulting in convection in the upper ocean. The opposite occurs in areas of net precipitation. Water vapour is the dominant greenhouse gas but it is controlled by temperature and in that respect it is part of the climate response or feedback system. All indications are that water vapour constitutes a positive feedback on climate, but the strength of the feedback is model sensitive. This is mostly due to different patterns of low/high-latitude temperature and resulting lapse rate changes since the combined water vapour lapse rate feedback is fairly robust. Water vapour is increasing rapidly in a warmer climate but theory and models suggest that global precipitation might be increasing much more slowly.
This has a number of important consequences for the hydrological cycle in a warmer climate, namely that areas with high precipitation rates today will have increased precipitation rates and areas with low precipitation will have reduced rates, making the hydrological cycle more extreme.

The increase in water vapour in a warmer climate is expected to lead to more intense precipitation and this is actually simulated by models. In the same way latent-heat-driven weather systems such as tropical cyclones are likely to be more intense in a warmer climate. This is also simulated by high-resolution climate models that at the same time show an overall reduction in the total number of tropical cyclones.

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