Appendix to Rebuttal to review comments on “Revisiting global hydrological cycle: Is it intensifying?”

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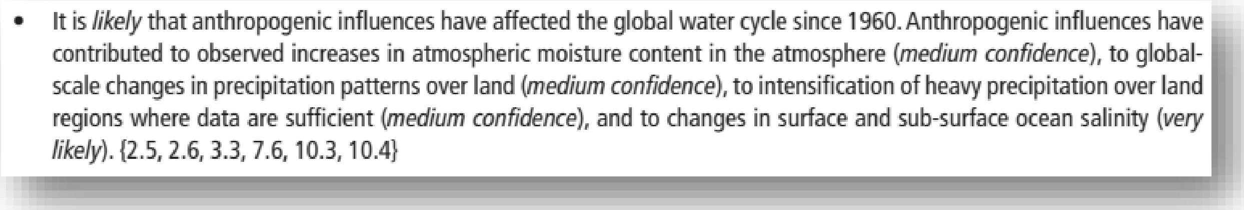
This Appendix contains copies of extracts of the IPCC AR5 WG1 Report in which the Clausius-Clapeyron equation, combined with the constancy of specific humidity, as well as the expected increase in precipitation and intensification of the hydrological cycle are mentioned.

Summary for Policymakers

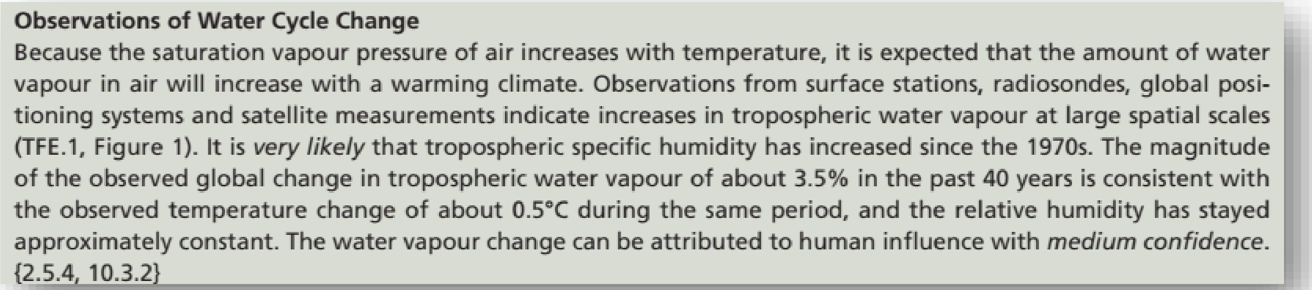
D.3 Detection and Attribution of Climate Change, p. 17



- It is *likely* that anthropogenic influences have affected the global water cycle since 1960. Anthropogenic influences have contributed to observed increases in atmospheric moisture content in the atmosphere (*medium confidence*), to global-scale changes in precipitation patterns over land (*medium confidence*), to intensification of heavy precipitation over land regions where data are sufficient (*medium confidence*), and to changes in surface and sub-surface ocean salinity (*very likely*). {2.5, 2.6, 3.3, 7.6, 10.3, 10.4}

Technical Summary

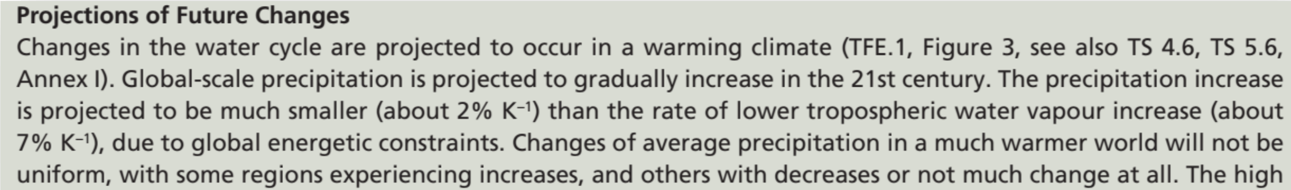
Thematic Focus Elements TFE.1 | Water Cycle Change, p. 42



Observations of Water Cycle Change

Because the saturation vapour pressure of air increases with temperature, it is expected that the amount of water vapour in air will increase with a warming climate. Observations from surface stations, radiosondes, global positioning systems and satellite measurements indicate increases in tropospheric water vapour at large spatial scales (TFE.1, Figure 1). It is *very likely* that tropospheric specific humidity has increased since the 1970s. The magnitude of the observed global change in tropospheric water vapour of about 3.5% in the past 40 years is consistent with the observed temperature change of about 0.5°C during the same period, and the relative humidity has stayed approximately constant. The water vapour change can be attributed to human influence with *medium confidence*. {2.5.4, 10.3.2}

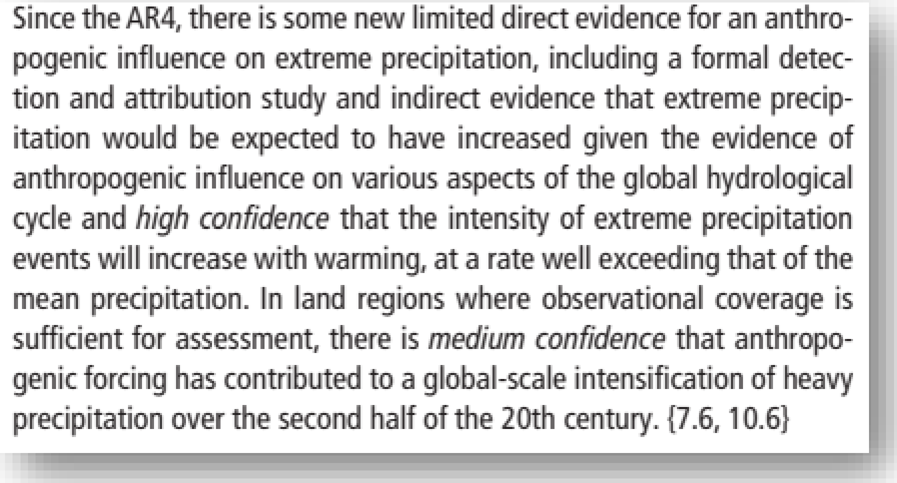
Thematic Focus Elements TFE.1 | Water Cycle Change, p. 44



Projections of Future Changes

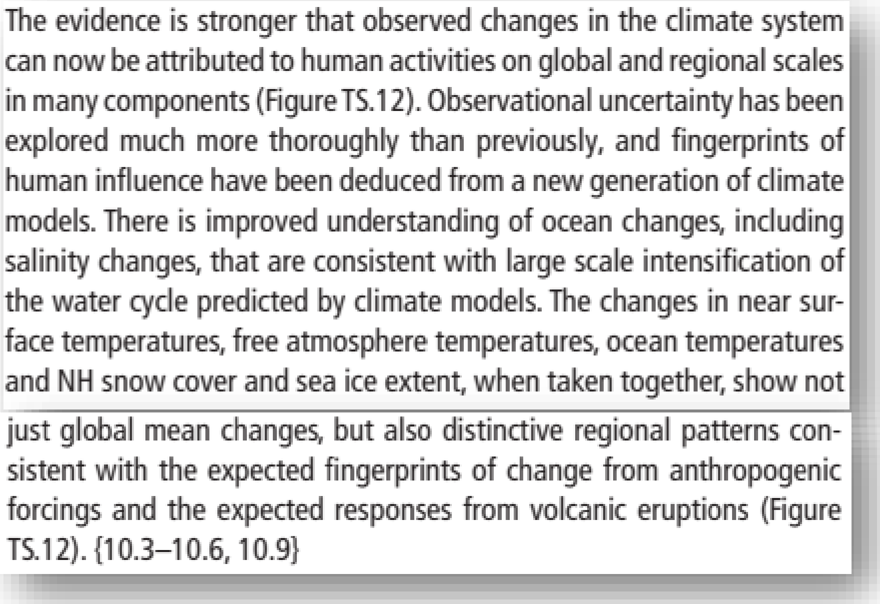
Changes in the water cycle are projected to occur in a warming climate (TFE.1, Figure 3, see also TS 4.6, TS 5.6, Annex I). Global-scale precipitation is projected to gradually increase in the 21st century. The precipitation increase is projected to be much smaller (about 2% K^{-1}) than the rate of lower tropospheric water vapour increase (about 7% K^{-1}), due to global energetic constraints. Changes of average precipitation in a much warmer world will not be uniform, with some regions experiencing increases, and others with decreases or not much change at all. The high

TS.4.7 Climate Extremes, p. 72



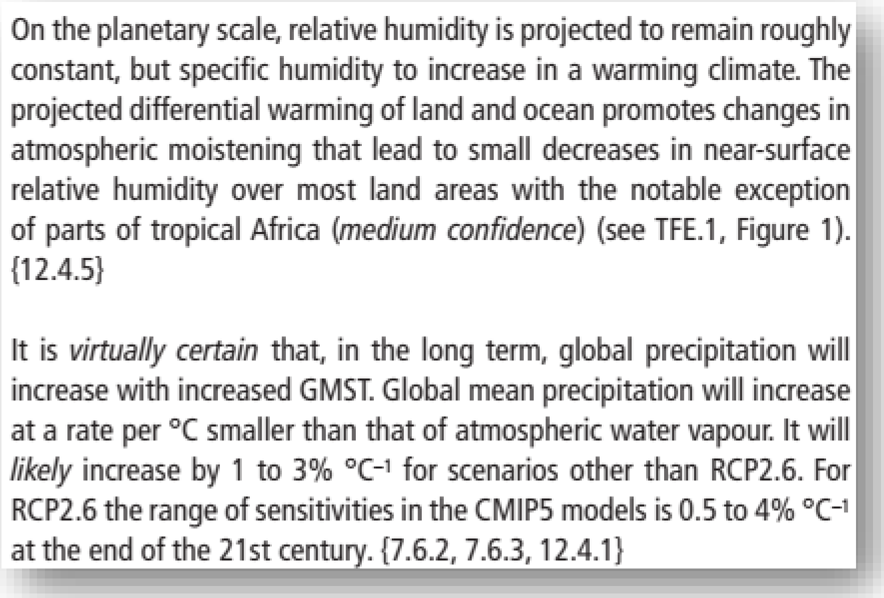
Since the AR4, there is some new limited direct evidence for an anthropogenic influence on extreme precipitation, including a formal detection and attribution study and indirect evidence that extreme precipitation would be expected to have increased given the evidence of anthropogenic influence on various aspects of the global hydrological cycle and *high confidence* that the intensity of extreme precipitation events will increase with warming, at a rate well exceeding that of the mean precipitation. In land regions where observational coverage is sufficient for assessment, there is *medium confidence* that anthropogenic forcing has contributed to a global-scale intensification of heavy precipitation over the second half of the 20th century. {7.6, 10.6}

TS.4.8 From Global to Regional, p. 73



The evidence is stronger that observed changes in the climate system can now be attributed to human activities on global and regional scales in many components (Figure TS.12). Observational uncertainty has been explored much more thoroughly than previously, and fingerprints of human influence have been deduced from a new generation of climate models. There is improved understanding of ocean changes, including salinity changes, that are consistent with large scale intensification of the water cycle predicted by climate models. The changes in near surface temperatures, free atmosphere temperatures, ocean temperatures and NH snow cover and sea ice extent, when taken together, show not just global mean changes, but also distinctive regional patterns consistent with the expected fingerprints of change from anthropogenic forcings and the expected responses from volcanic eruptions (Figure TS.12). {10.3–10.6, 10.9}

Section TS.5.5.4 Projected Long-term Changes in the Water Cycle, p. 91

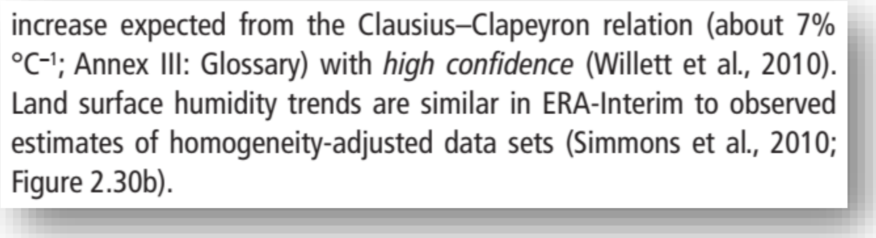


On the planetary scale, relative humidity is projected to remain roughly constant, but specific humidity to increase in a warming climate. The projected differential warming of land and ocean promotes changes in atmospheric moistening that lead to small decreases in near-surface relative humidity over most land areas with the notable exception of parts of tropical Africa (*medium confidence*) (see TFE.1, Figure 1). {12.4.5}

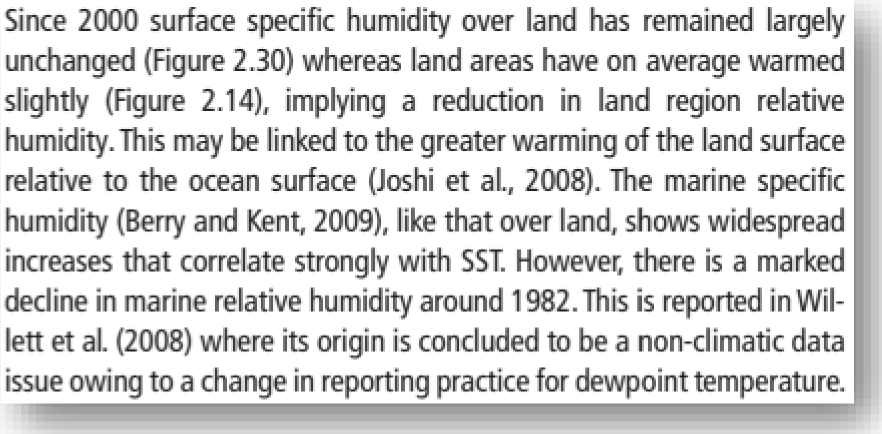
It is *virtually certain* that, in the long term, global precipitation will increase with increased GMST. Global mean precipitation will increase at a rate per °C smaller than that of atmospheric water vapour. It will *likely* increase by 1 to 3% $°C^{-1}$ for scenarios other than RCP2.6. For RCP2.6 the range of sensitivities in the CMIP5 models is 0.5 to 4% $°C^{-1}$ at the end of the 21st century. {7.6.2, 7.6.3, 12.4.1}

Chapter 2 Observations: Atmosphere and Surface

Section 2.5.4 Surface Humidity, p. 206

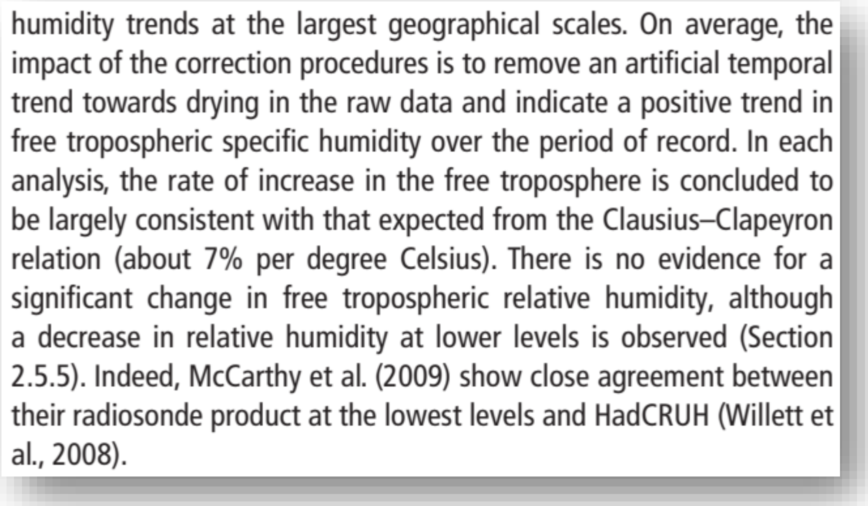


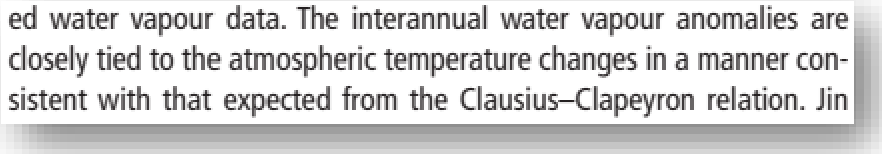
increase expected from the Clausius–Clapeyron relation (about 7% $°C^{-1}$; Annex III: Glossary) with *high confidence* (Willett et al., 2010). Land surface humidity trends are similar in ERA-Interim to observed estimates of homogeneity-adjusted data sets (Simmons et al., 2010; Figure 2.30b).

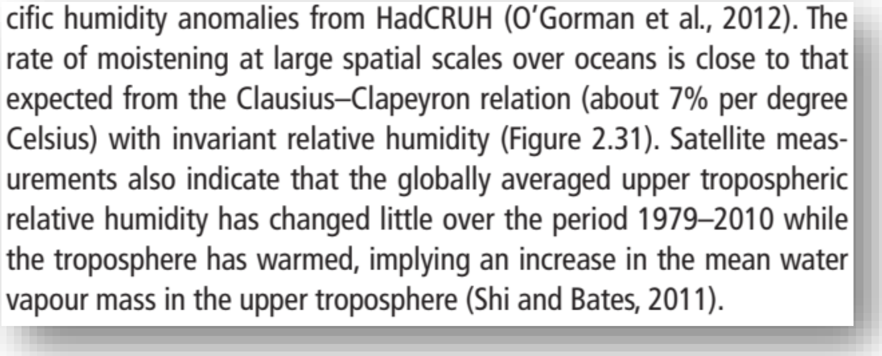


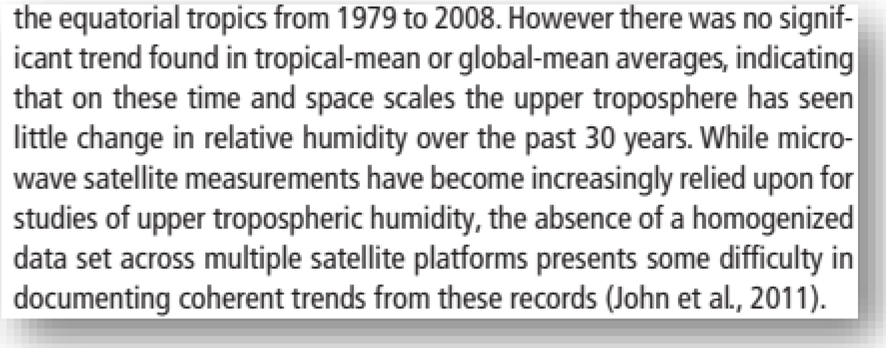
Since 2000 surface specific humidity over land has remained largely unchanged (Figure 2.30) whereas land areas have on average warmed slightly (Figure 2.14), implying a reduction in land region relative humidity. This may be linked to the greater warming of the land surface relative to the ocean surface (Joshi et al., 2008). The marine specific humidity (Berry and Kent, 2009), like that over land, shows widespread increases that correlate strongly with SST. However, there is a marked decline in marine relative humidity around 1982. This is reported in Willett et al. (2008) where its origin is concluded to be a non-climatic data issue owing to a change in reporting practice for dewpoint temperature.

2.5.5 Tropospheric Humidity, p. 207

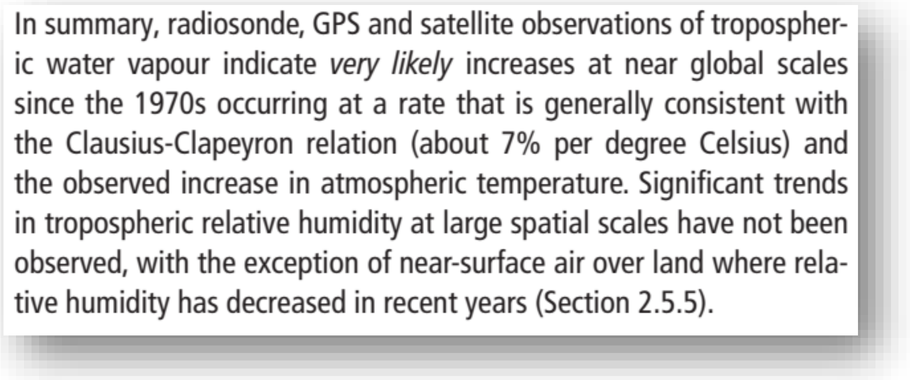

humidity trends at the largest geographical scales. On average, the impact of the correction procedures is to remove an artificial temporal trend towards drying in the raw data and indicate a positive trend in free tropospheric specific humidity over the period of record. In each analysis, the rate of increase in the free troposphere is concluded to be largely consistent with that expected from the Clausius–Clapeyron relation (about 7% per degree Celsius). There is no evidence for a significant change in free tropospheric relative humidity, although a decrease in relative humidity at lower levels is observed (Section 2.5.5). Indeed, McCarthy et al. (2009) show close agreement between their radiosonde product at the lowest levels and HadCRUH (Willett et al., 2008).


ed water vapour data. The interannual water vapour anomalies are closely tied to the atmospheric temperature changes in a manner consistent with that expected from the Clausius–Clapeyron relation. Jin


cific humidity anomalies from HadCRUH (O'Gorman et al., 2012). The rate of moistening at large spatial scales over oceans is close to that expected from the Clausius–Clapeyron relation (about 7% per degree Celsius) with invariant relative humidity (Figure 2.31). Satellite measurements also indicate that the globally averaged upper tropospheric relative humidity has changed little over the period 1979–2010 while the troposphere has warmed, implying an increase in the mean water vapour mass in the upper troposphere (Shi and Bates, 2011).

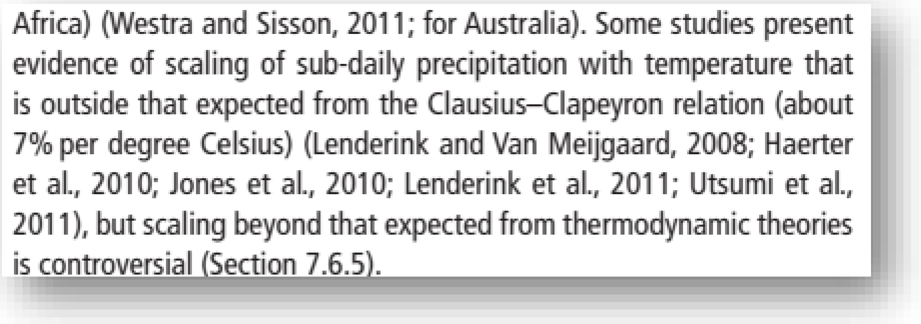

the equatorial tropics from 1979 to 2008. However there was no significant trend found in tropical-mean or global-mean averages, indicating that on these time and space scales the upper troposphere has seen little change in relative humidity over the past 30 years. While microwave satellite measurements have become increasingly relied upon for studies of upper tropospheric humidity, the absence of a homogenized data set across multiple satellite platforms presents some difficulty in documenting coherent trends from these records (John et al., 2011).

2.5.5 Tropospheric Humidity, p. 208



In summary, radiosonde, GPS and satellite observations of tropospheric water vapour indicate *very likely* increases at near global scales since the 1970s occurring at a rate that is generally consistent with the Clausius-Clapeyron relation (about 7% per degree Celsius) and the observed increase in atmospheric temperature. Significant trends in tropospheric relative humidity at large spatial scales have not been observed, with the exception of near-surface air over land where relative humidity has decreased in recent years (Section 2.5.5).

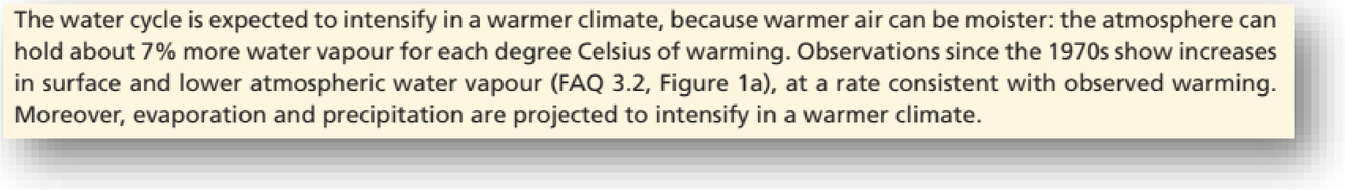
2.6.1 Temperature Extremes, p. 213



Africa) (Westra and Sisson, 2011; for Australia). Some studies present evidence of scaling of sub-daily precipitation with temperature that is outside that expected from the Clausius–Clapeyron relation (about 7% per degree Celsius) (Lenderink and Van Meijgaard, 2008; Haerter et al., 2010; Jones et al., 2010; Lenderink et al., 2011; Utsumi et al., 2011), but scaling beyond that expected from thermodynamic theories is controversial (Section 7.6.5).

Chapter 3 Observations: Ocean

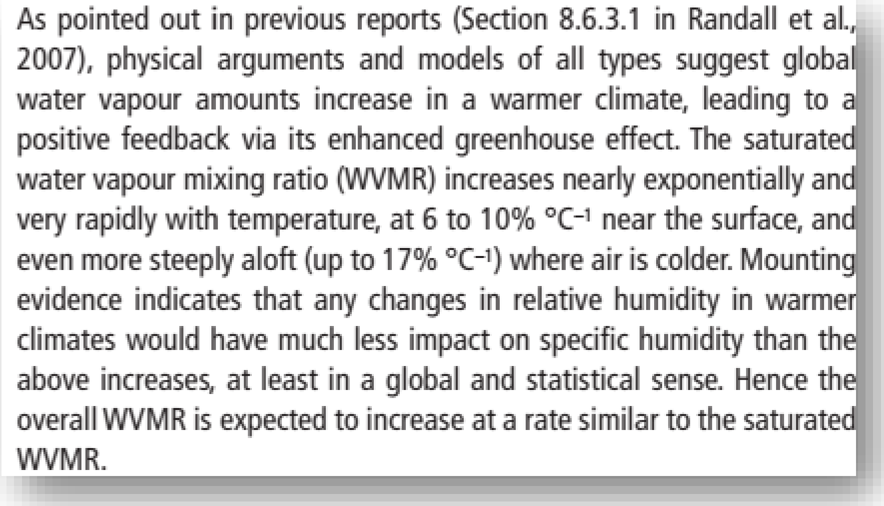
Frequently Asked Questions FAQ 3.2 | Is There Evidence for Changes in the Earth’s Water Cycle?, p. 269



The water cycle is expected to intensify in a warmer climate, because warmer air can be moister: the atmosphere can hold about 7% more water vapour for each degree Celsius of warming. Observations since the 1970s show increases in surface and lower atmospheric water vapour (FAQ 3.2, Figure 1a), at a rate consistent with observed warming. Moreover, evaporation and precipitation are projected to intensify in a warmer climate.

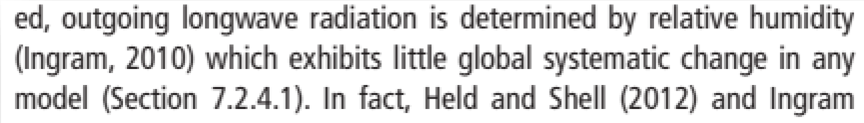
Chapter 7 Clouds and Aerosols

7.2.4 Water Vapour and Lapse Rate Feedbacks, p. 586



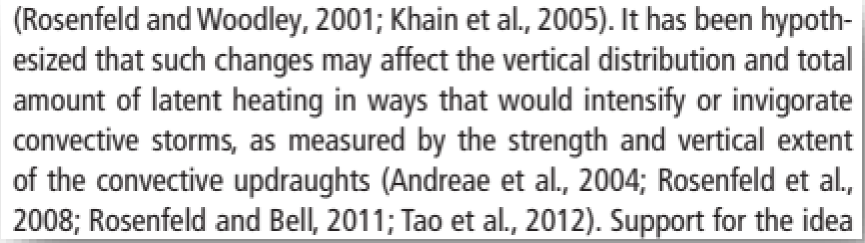
As pointed out in previous reports (Section 8.6.3.1 in Randall et al., 2007), physical arguments and models of all types suggest global water vapour amounts increase in a warmer climate, leading to a positive feedback via its enhanced greenhouse effect. The saturated water vapour mixing ratio (WVMR) increases nearly exponentially and very rapidly with temperature, at 6 to 10% °C^{-1} near the surface, and even more steeply aloft (up to 17% °C^{-1}) where air is colder. Mounting evidence indicates that any changes in relative humidity in warmer climates would have much less impact on specific humidity than the above increases, at least in a global and statistical sense. Hence the overall WVMR is expected to increase at a rate similar to the saturated WVMR.

7.2.4 Water Vapour and Lapse Rate Feedbacks, p. 587



ed, outgoing longwave radiation is determined by relative humidity (Ingram, 2010) which exhibits little global systematic change in any model (Section 7.2.4.1). In fact, Held and Shell (2012) and Ingram

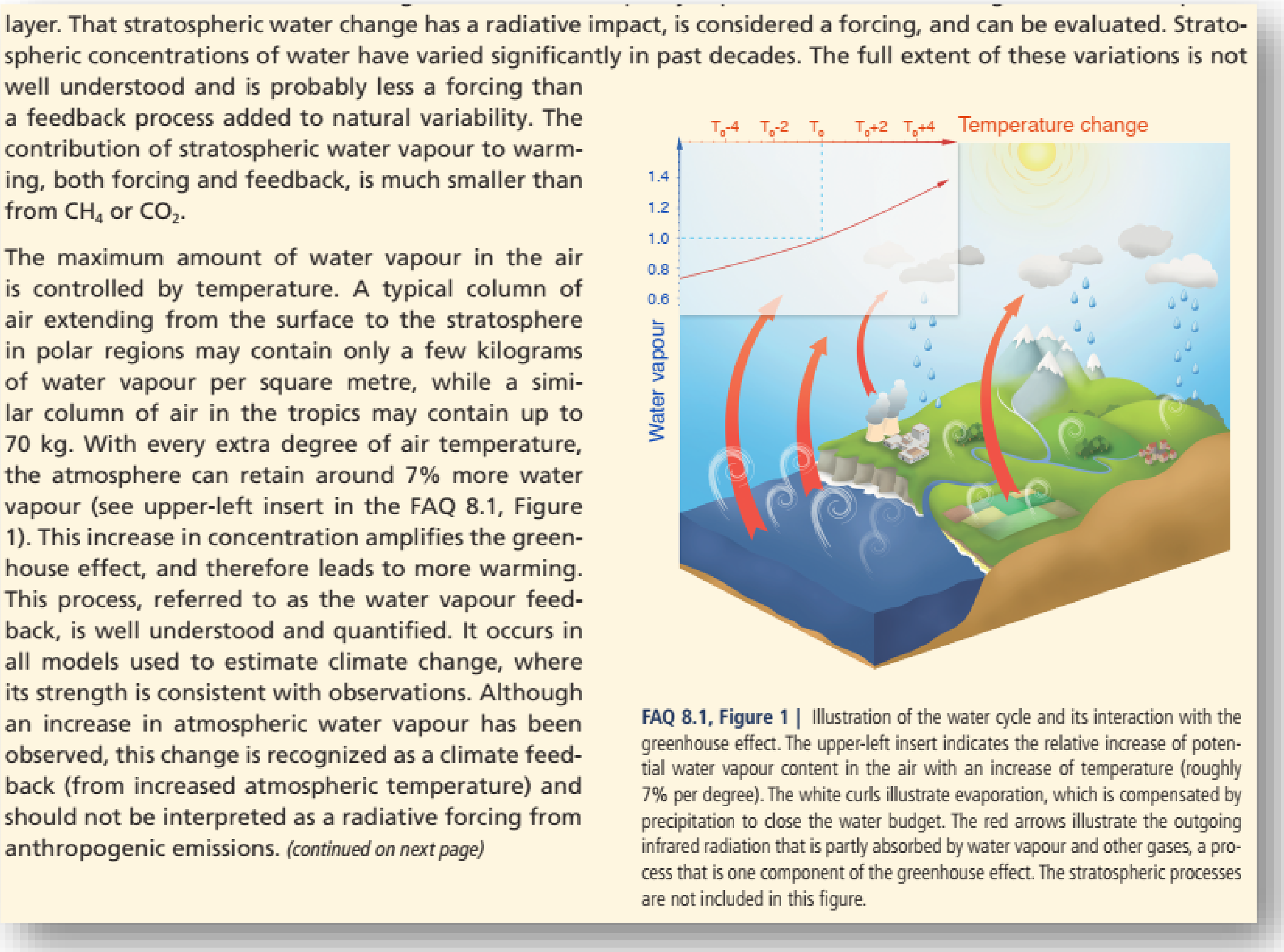
7.6.4 Effects of Aerosol–Cloud Interactions on Precipitation, p. 625



(Rosenfeld and Woodley, 2001; Khain et al., 2005). It has been hypothesized that such changes may affect the vertical distribution and total amount of latent heating in ways that would intensify or invigorate convective storms, as measured by the strength and vertical extent of the convective updraughts (Andreae et al., 2004; Rosenfeld et al., 2008; Rosenfeld and Bell, 2011; Tao et al., 2012). Support for the idea

Chapter 8 Anthropogenic and Natural Radiative Forcing

Frequently Asked Questions FAQ 8.1 | How Important Is Water Vapour to Climate Change?, p. 666



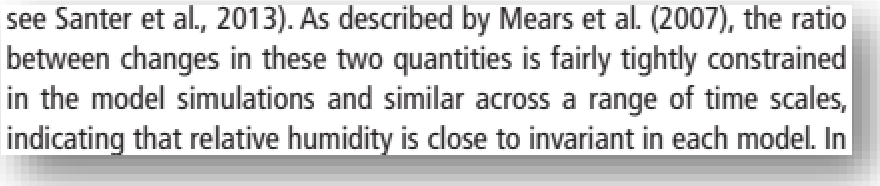
layer. That stratospheric water change has a radiative impact, is considered a forcing, and can be evaluated. Stratospheric concentrations of water have varied significantly in past decades. The full extent of these variations is not well understood and is probably less a forcing than a feedback process added to natural variability. The contribution of stratospheric water vapour to warming, both forcing and feedback, is much smaller than from CH_4 or CO_2.

The maximum amount of water vapour in the air is controlled by temperature. A typical column of air extending from the surface to the stratosphere in polar regions may contain only a few kilograms of water vapour per square metre, while a similar column of air in the tropics may contain up to 70 kg. With every extra degree of air temperature, the atmosphere can retain around 7% more water vapour (see upper-left insert in the FAQ 8.1, Figure 1). This increase in concentration amplifies the greenhouse effect, and therefore leads to more warming. This process, referred to as the water vapour feedback, is well understood and quantified. It occurs in all models used to estimate climate change, where its strength is consistent with observations. Although an increase in atmospheric water vapour has been observed, this change is recognized as a climate feedback (from increased atmospheric temperature) and should not be interpreted as a radiative forcing from anthropogenic emissions. *(continued on next page)*

FAQ 8.1, Figure 1 | Illustration of the water cycle and its interaction with the greenhouse effect. The upper-left insert indicates the relative increase of potential water vapour content in the air with an increase of temperature (roughly 7% per degree). The white curls illustrate evaporation, which is compensated by precipitation to close the water budget. The red arrows illustrate the outgoing infrared radiation that is partly absorbed by water vapour and other gases, a process that is one component of the greenhouse effect. The stratospheric processes are not included in this figure.

Chapter 9 Evaluation of Climate Models

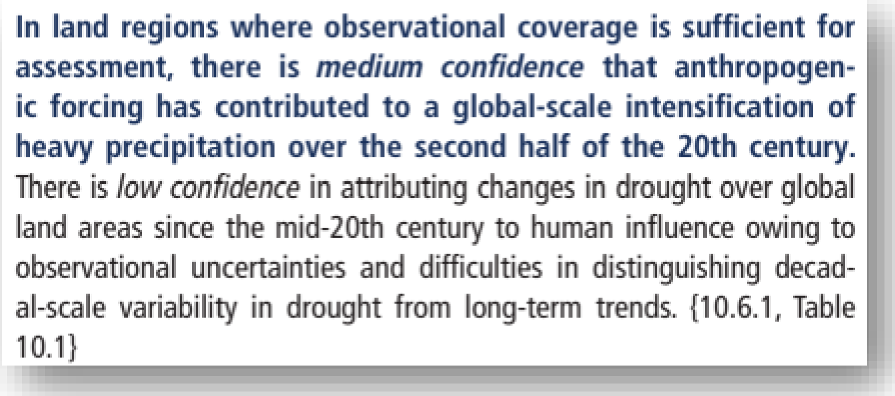
9.4 Simulation of Recent and Longer-Term Records in Global Models, p. 774



see Santer et al., 2013). As described by Mears et al. (2007), the ratio between changes in these two quantities is fairly tightly constrained in the model simulations and similar across a range of time scales, indicating that relative humidity is close to invariant in each model. In

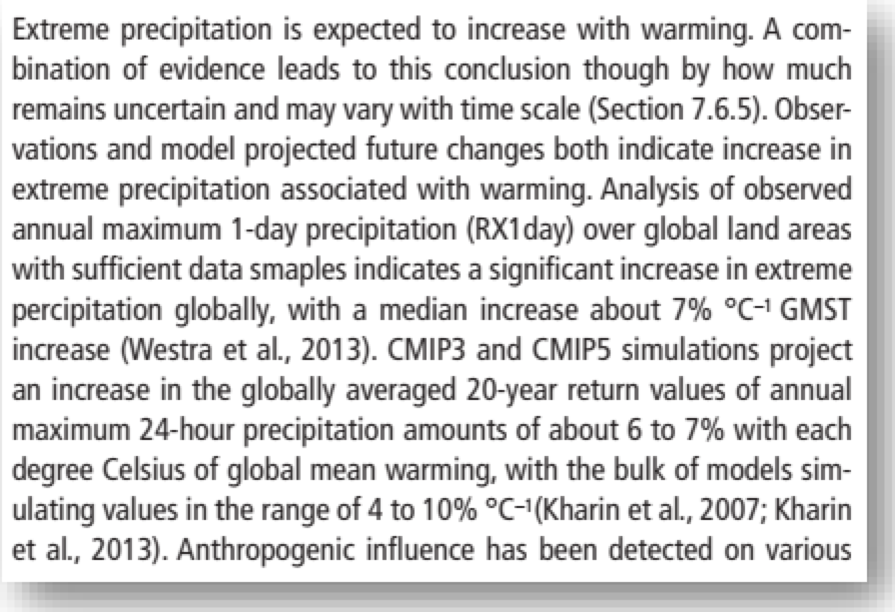
Chapter 10 Detection and Attribution of Climate Change: from Global to Regional

Executive Summary, p. 871

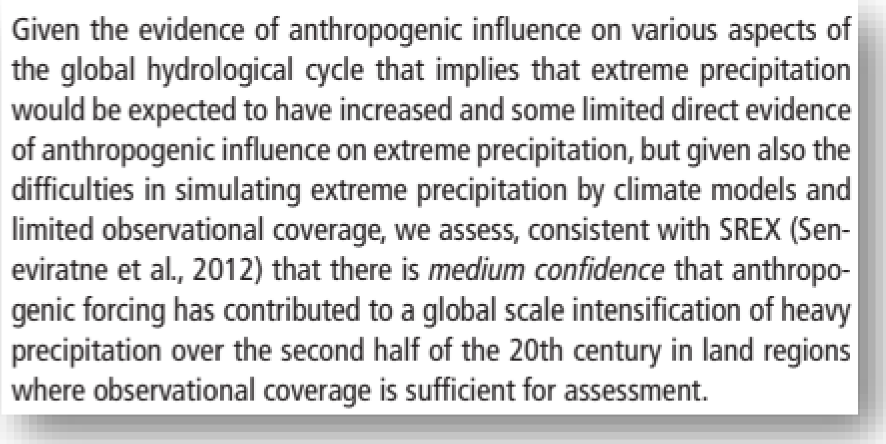


In land regions where observational coverage is sufficient for assessment, there is *medium confidence* that anthropogenic forcing has contributed to a global-scale intensification of heavy precipitation over the second half of the 20th century. There is *low confidence* in attributing changes in drought over global land areas since the mid-20th century to human influence owing to observational uncertainties and difficulties in distinguishing decadal-scale variability in drought from long-term trends. {10.6.1, Table 10.1}

10.6.1 Attribution of Changes in Frequency/Occurrence and Intensity of Extremes, p. 912

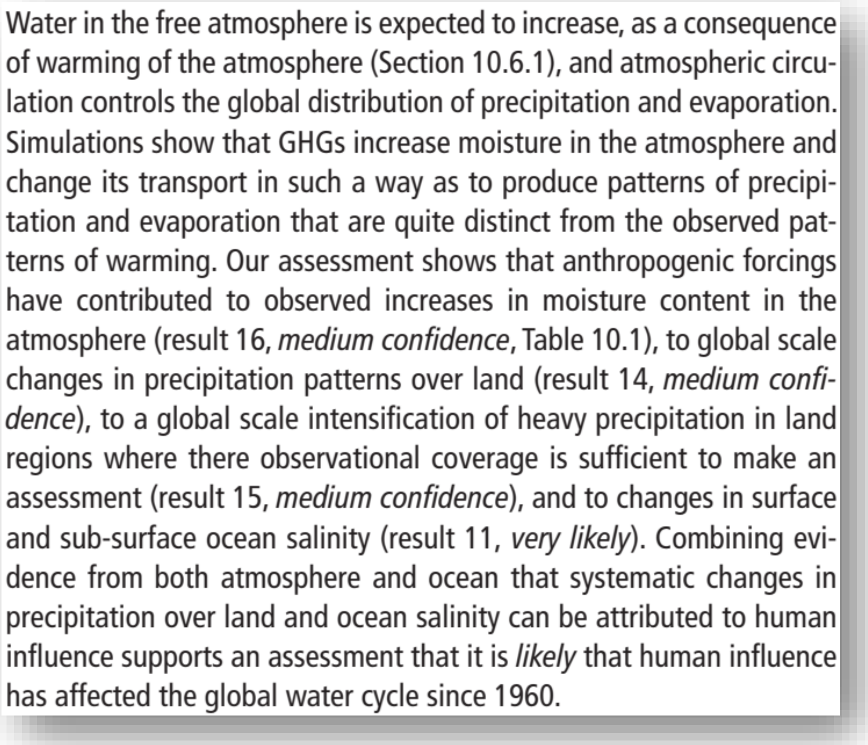


Extreme precipitation is expected to increase with warming. A combination of evidence leads to this conclusion though by how much remains uncertain and may vary with time scale (Section 7.6.5). Observations and model projected future changes both indicate increase in extreme precipitation associated with warming. Analysis of observed annual maximum 1-day precipitation (RX1day) over global land areas with sufficient data smaples indicates a significant increase in extreme percipitation globally, with a median increase about 7% °C^{-1} GMST increase (Westra et al., 2013). CMIP3 and CMIP5 simulations project an increase in the globally averaged 20-year return values of annual maximum 24-hour precipitation amounts of about 6 to 7% with each degree Celsius of global mean warming, with the bulk of models simulating values in the range of 4 to 10% °C^{-1}(Kharin et al., 2007; Kharin et al., 2013). Anthropogenic influence has been detected on various

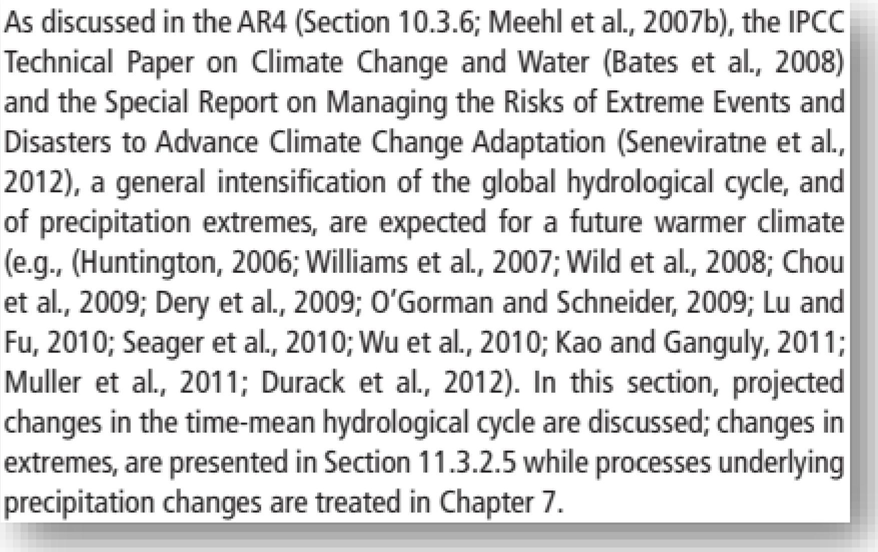


Given the evidence of anthropogenic influence on various aspects of the global hydrological cycle that implies that extreme precipitation would be expected to have increased and some limited direct evidence of anthropogenic influence on extreme precipitation, but given also the difficulties in simulating extreme precipitation by climate models and limited observational coverage, we assess, consistent with SREX (Seneviratne et al., 2012) that there is *medium confidence* that anthropogenic forcing has contributed to a global scale intensification of heavy precipitation over the second half of the 20th century in land regions where observational coverage is sufficient for assessment.

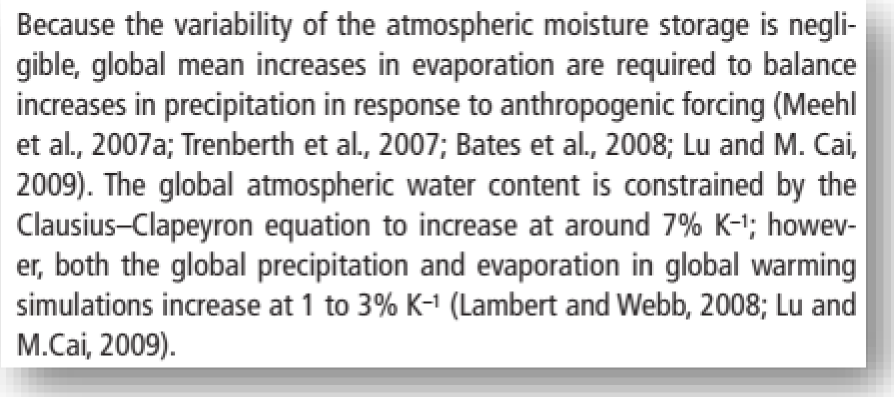
10.9.1 Multi-variable Approaches, p. 931


Water in the free atmosphere is expected to increase, as a consequence of warming of the atmosphere (Section 10.6.1), and atmospheric circulation controls the global distribution of precipitation and evaporation. Simulations show that GHGs increase moisture in the atmosphere and change its transport in such a way as to produce patterns of precipitation and evaporation that are quite distinct from the observed patterns of warming. Our assessment shows that anthropogenic forcings have contributed to observed increases in moisture content in the atmosphere (result 16, *medium confidence*, Table 10.1), to global scale changes in precipitation patterns over land (result 14, *medium confidence*), to a global scale intensification of heavy precipitation in land regions where there observational coverage is sufficient to make an assessment (result 15, *medium confidence*), and to changes in surface and sub-surface ocean salinity (result 11, *very likely*). Combining evidence from both atmosphere and ocean that systematic changes in precipitation over land and ocean salinity can be attributed to human influence supports an assessment that it is *likely* that human influence has affected the global water cycle since 1960.

11.3.2 Near-term Projected Changes in the Atmosphere and Land Surface, p. 984

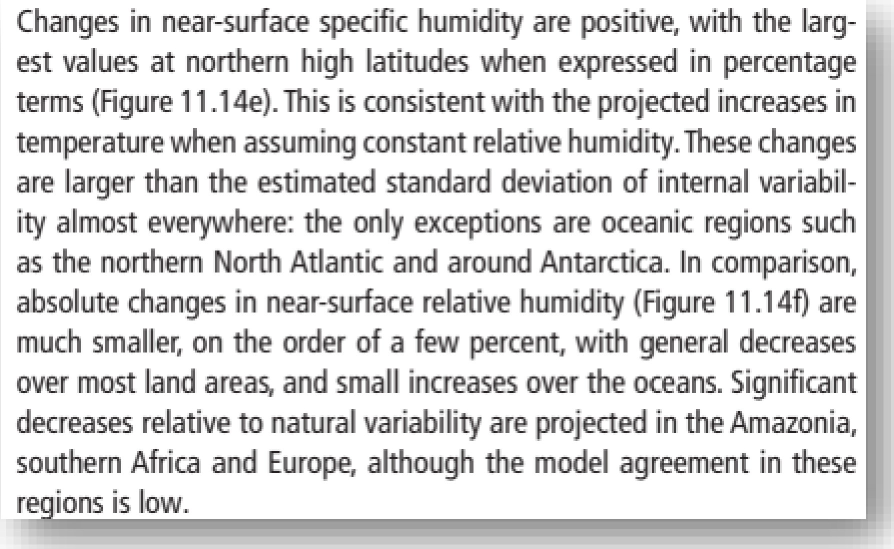

As discussed in the AR4 (Section 10.3.6; Meehl et al., 2007b), the IPCC Technical Paper on Climate Change and Water (Bates et al., 2008) and the Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (Seneviratne et al., 2012), a general intensification of the global hydrological cycle, and of precipitation extremes, are expected for a future warmer climate (e.g., (Huntington, 2006; Williams et al., 2007; Wild et al., 2008; Chou et al., 2009; Dery et al., 2009; O'Gorman and Schneider, 2009; Lu and Fu, 2010; Seager et al., 2010; Wu et al., 2010; Kao and Ganguly, 2011; Muller et al., 2011; Durack et al., 2012). In this section, projected changes in the time-mean hydrological cycle are discussed; changes in extremes, are presented in Section 11.3.2.5 while processes underlying precipitation changes are treated in Chapter 7.

11.3.2 Near-term Projected Changes in the Atmosphere and Land Surface, p. 986



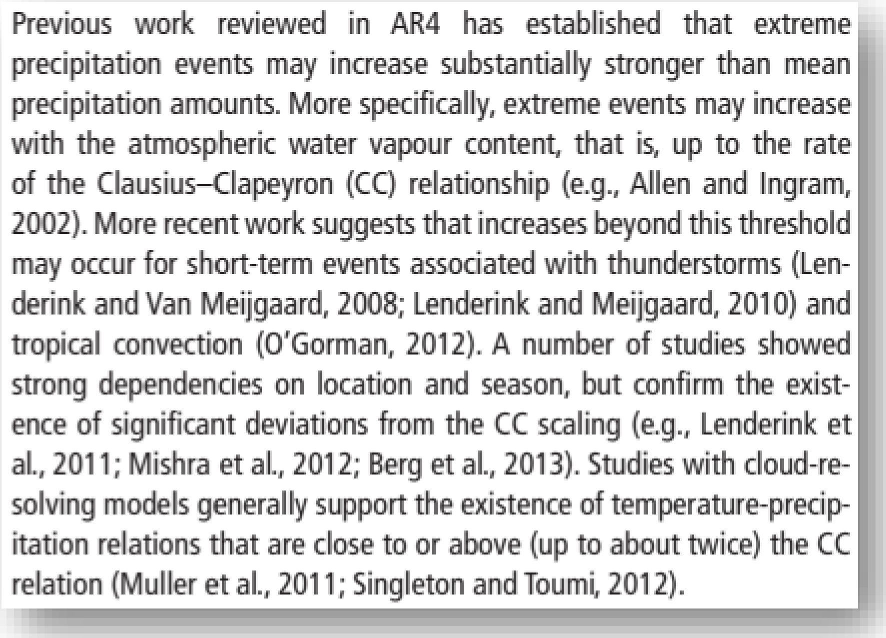
Because the variability of the atmospheric moisture storage is negligible, global mean increases in evaporation are required to balance increases in precipitation in response to anthropogenic forcing (Meehl et al., 2007a; Trenberth et al., 2007; Bates et al., 2008; Lu and M. Cai, 2009). The global atmospheric water content is constrained by the Clausius–Clapeyron equation to increase at around 7% K^{-1}; however, both the global precipitation and evaporation in global warming simulations increase at 1 to 3% K^{-1} (Lambert and Webb, 2008; Lu and M.Cai, 2009).

11.3.2 Near-term Projected Changes in the Atmosphere and Land Surface, p. 988



Changes in near-surface specific humidity are positive, with the largest values at northern high latitudes when expressed in percentage terms (Figure 11.14e). This is consistent with the projected increases in temperature when assuming constant relative humidity. These changes are larger than the estimated standard deviation of internal variability almost everywhere: the only exceptions are oceanic regions such as the northern North Atlantic and around Antarctica. In comparison, absolute changes in near-surface relative humidity (Figure 11.14f) are much smaller, on the order of a few percent, with general decreases over most land areas, and small increases over the oceans. Significant decreases relative to natural variability are projected in the Amazonia, southern Africa and Europe, although the model agreement in these regions is low.

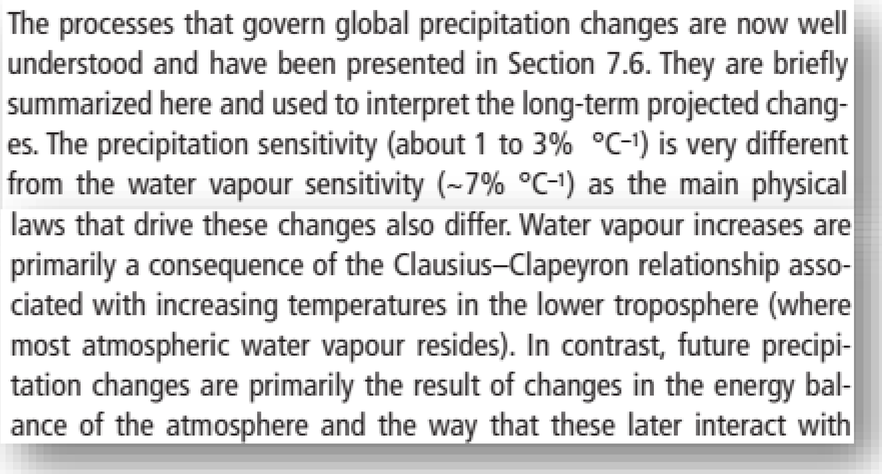
11.3.2 Near-term Projected Changes in the Atmosphere and Land Surface,p. 992



Previous work reviewed in AR4 has established that extreme precipitation events may increase substantially stronger than mean precipitation amounts. More specifically, extreme events may increase with the atmospheric water vapour content, that is, up to the rate of the Clausius–Clapeyron (CC) relationship (e.g., Allen and Ingram, 2002). More recent work suggests that increases beyond this threshold may occur for short-term events associated with thunderstorms (Lenderink and Van Meijgaard, 2008; Lenderink and Meijgaard, 2010) and tropical convection (O'Gorman, 2012). A number of studies showed strong dependencies on location and season, but confirm the existence of significant deviations from the CC scaling (e.g., Lenderink et al., 2011; Mishra et al., 2012; Berg et al., 2013). Studies with cloud-resolving models generally support the existence of temperature-precipitation relations that are close to or above (up to about twice) the CC relation (Muller et al., 2011; Singleton and Toumi, 2012).

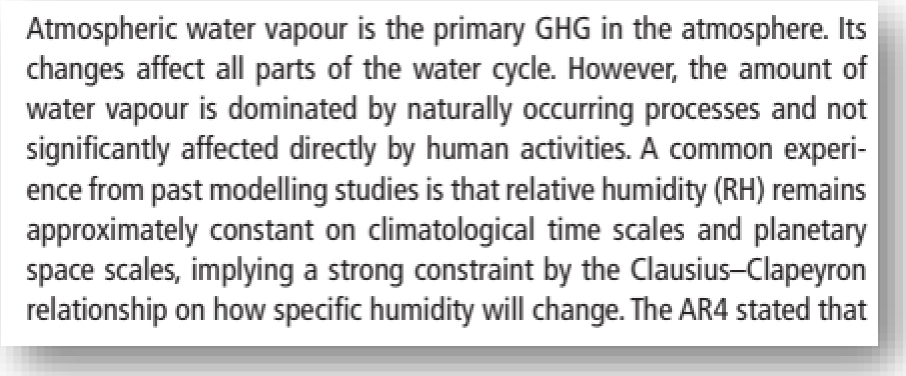
Chapter 12 Long-term Climate Change: Projections, Commitments and Irreversibility

12.4.1 Time-Evolving Global Quantities, pp. 1055-1056



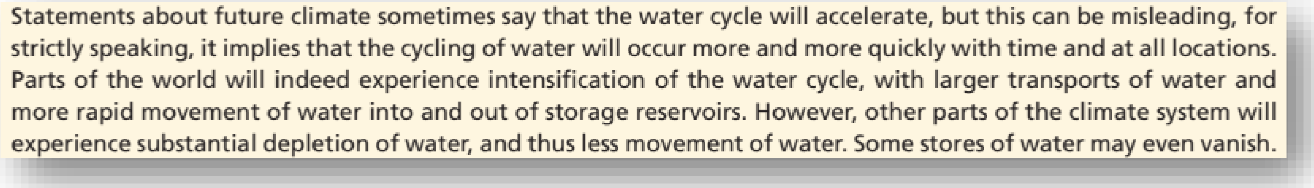
The processes that govern global precipitation changes are now well understood and have been presented in Section 7.6. They are briefly summarized here and used to interpret the long-term projected changes. The precipitation sensitivity (about 1 to 3% $^{\circ}C^{-1}$) is very different from the water vapour sensitivity (~7% $^{\circ}C^{-1}$) as the main physical laws that drive these changes also differ. Water vapour increases are primarily a consequence of the Clausius–Clapeyron relationship associated with increasing temperatures in the lower troposphere (where most atmospheric water vapour resides). In contrast, future precipitation changes are primarily the result of changes in the energy balance of the atmosphere and the way that these later interact with

12.4.5 Changes in the Water Cycle, p. 1076



Atmospheric water vapour is the primary GHG in the atmosphere. Its changes affect all parts of the water cycle. However, the amount of water vapour is dominated by naturally occurring processes and not significantly affected directly by human activities. A common experience from past modelling studies is that relative humidity (RH) remains approximately constant on climatological time scales and planetary space scales, implying a strong constraint by the Clausius–Clapeyron relationship on how specific humidity will change. The AR4 stated that

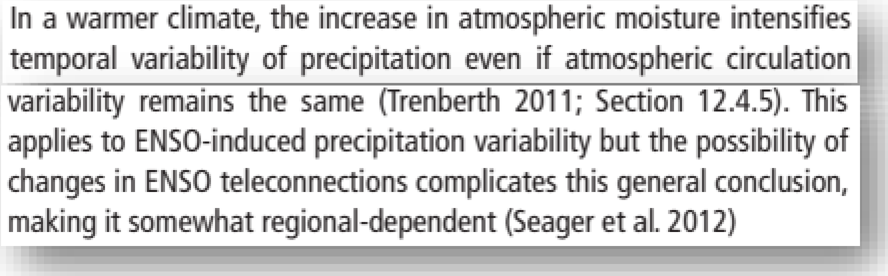
FAQ 12.2 | How Will the Earth's Water Cycle Change?, p. 1084



Statements about future climate sometimes say that the water cycle will accelerate, but this can be misleading, for strictly speaking, it implies that the cycling of water will occur more and more quickly with time and at all locations. Parts of the world will indeed experience intensification of the water cycle, with larger transports of water and more rapid movement of water into and out of storage reservoirs. However, other parts of the climate system will experience substantial depletion of water, and thus less movement of water. Some stores of water may even vanish.

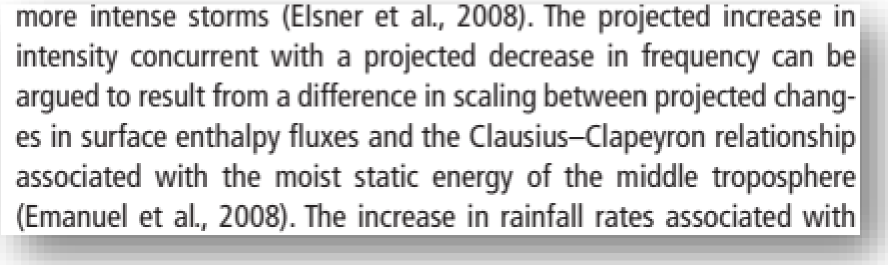
Chapter 14 Climate Phenomena and their Relevance for Future Regional Climate Change

14.4.3 Teleconnections, p. 1243



In a warmer climate, the increase in atmospheric moisture intensifies temporal variability of precipitation even if atmospheric circulation variability remains the same (Trenberth 2011; Section 12.4.5). This applies to ENSO-induced precipitation variability but the possibility of changes in ENSO teleconnections complicates this general conclusion, making it somewhat regional-dependent (Seager et al. 2012)

14.6.1 Tropical Cyclones, p. 1249



more intense storms (Elsner et al., 2008). The projected increase in intensity concurrent with a projected decrease in frequency can be argued to result from a difference in scaling between projected changes in surface enthalpy fluxes and the Clausius–Clapeyron relationship associated with the moist static energy of the middle troposphere (Emanuel et al., 2008). The increase in rainfall rates associated with