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The Role of Water Vapour in Earth's Energy Flows

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Abstract Water vapour modulates energy flows in Earth's climate system through transfer of latent heat by evaporation and condensation and by modifying the flows of radiative energy both in the longwave and shortwave portions of the electromagnetic spectrum. This article summarizes the role of water vapour in Earth's energy flows with particular emphasis on (1) the powerful thermodynamic constraint of the Clausius Clapeyron equation, (2) dynamical controls on humidity above the boundary layer (or free-troposphere), (3) uncertainty in continuum absorption in the relatively transparent "window" regions of the radiative spectrum and (4) implications for changes in the atmospheric hydrological cycle.

Keywords Water vapour · Hydrological cycle · Radiative processes · Climate

1 Introduction

Water vapour is of central importance to energy flows within the climate system, by modulating the transmission of radiative energy between the surface, atmosphere and space and also through transferring latent heat from the surface (evaporation) to the atmosphere (precipitation)[1] following transport of moisture within the atmosphere (Fig. 1). There are many aspects of these processes that are well understood, based upon robust physics, detailed process modelling and measurements ranging from laboratory experiments up to satellite observations of the entire globe (e.g., Held and Soden 2006; Sherwood et al. 2010a, b). One of the fundamental controls on the climate system is the Clausius Clapeyron equation which provides a powerful constraint on how saturated moisture content varies with air temperature:

[1] Latent heat released by condensation is retained in the atmosphere only after the water is removed by precipitation to the surface before re-evaporation in the atmosphere can occur.

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$$\frac{1}{q_s}\frac{dq_s}{dT} \approx \frac{1}{e_s}\frac{de_s}{dT} = \frac{L}{R_v T^2} = \begin{cases} 0.14\,\mathrm{K}^{-1} & \mathrm{T} = 200\,\mathrm{K} \\ 0.07\,\mathrm{K}^{-1} & \mathrm{T} = 273\,\mathrm{K}, \\ 0.06\,\mathrm{K}^{-1} & \mathrm{T} = 300\,\mathrm{K} \end{cases} \quad (1)$$

where q_s is the saturation specific humidity in kg water vapour per kg moist air, e_s is the saturation water vapour pressure (Pa), T is air temperature (K), L is the latent heat of vapourisation (2.5×10^6 J kg^{-1}), R_v is the gas constant for water vapour (461 J K^{-1} kg^{-1}) and the first term approximates to the second term[2]. Equation 1 therefore predicts increases in water vapour of order 6–7%/K for temperatures close to the surface assuming fixed relative humidity; further discussion is given by O'Gorman and Muller (2010).

Observations and modelling indicate that column integrated water vapour, averaged over sufficiently large scales, increases approximately exponentially with atmospheric temperature (Raval and Ramanathan 1989) as predicted by (1). The absorption of infra-red radiation by water vapour increases approximately in proportion to the logarithm of its concentration. These two powerful constraints generate an amplifying effect on changes in Earth's climate, enhancing the response of surface temperature to a radiative forcing or internal variability, and the resultant positive water vapour feedback is relatively "forgiving" in the sense that substantial excursions away from these basic physical constraints are required to alter its nature.

2 Radiative effects of water vapour

Absorption of radiation by water vapour in distinct bands across the electromagnetic spectrum, relating to vibrational and rotational modes of molecular excitation, is reasonably well characterised by detailed measurements and theory. Nevertheless, there remains a question as to the physical basis of radiative transfer away from the absorption line centres, important for the atmospheric "windows" in which radiative energy is more able to pass relatively unimpeded through the atmosphere compared to band centres. Although the continuum absorption in these windows, and its dependence on pressure and temperature, is now much better observed and characterised, there remains a lively debate on the underlying physical causes of this continuum. The historical perspective underpinning the development of a theory of water vapour continuum absorption has led to recent developments and experimental campaigns leading to new insights into this uncertain aspect of how water vapour influences the flows of radiative energy through the atmosphere (Shine et al. 2012). Although improved representation of the water vapour continuum is likely to reduce uncertainty in Earth's radiative energy budget only marginally, it may have implications for the retrieval of physical quantities from space and therefore how we observe Earth's climate system. There also remain important questions as to the consistency of water vapour absorption of solar radiation in climate models, with implications for responses of the hydrological cycle (Takahashi 2009).

3 Dynamical controls on the water vapour greenhouse effect

While the radiative effects of water vapour contribute uncertainty to the simulation of radiative fluxes, a greater source of uncertainty in simulating radiative fluxes regionally is

[2] The first term is larger than the second term by a factor $q_s p/\epsilon e_s = p/(p - e_s(1-\epsilon)) = 1 + q_s((1/\epsilon) - 1) \sim 1 + 0.6 q_s$ assuming fixed pressure, where $\varepsilon = 0.622$ is the ratio of gas constants for dry air and water vapour. For a surface pressure of 1,000 hPa and using the August−Roche–Magnus empirical approximation for $e_s(T)$, the first term exceeds the second term by around 0.2% at 273 K and by 1% at 300 K.

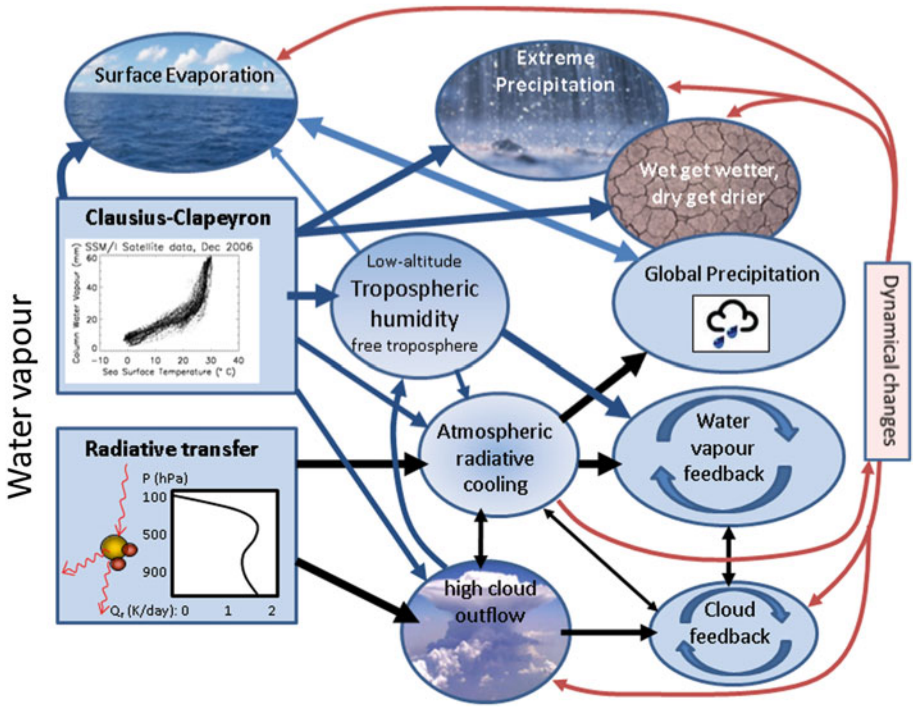

Fig. 1 The role of water vapour in Earth's energy flows: a simplistic schematic representation of some of the links between water vapour and energetic processes in the climate system. *Arrow* colours denote the primary driving physical process, including radiative transfer (*black*), thermodynamics (*blue*) and dynamics (*red*)

the distribution and concentration of water vapour throughout the atmosphere. The maintenance of the present-day distribution of relative humidity (RH = e/e_s), a diagnostic of how close the atmospheric water vapour pressure (e) is to the saturation vapour pressure (often expressed as a percentage), is also fundamental to positive water vapour feedback. Relative humidity within the subsiding branches of the tropical circulation is crucial in modulating the emission of infra-red radiation to space (Spencer and Braswell 1997; Allan et al. 1999; Brogniez et al. 2005).

The present day distribution of humidity is reasonably well approximated using a "point of last saturation" perspective, specifically that the amount of water vapour is determined by the temperature at which the considered parcel of air last experienced 100% relative humidity (Pierrehumbert 1998; Sherwood et al. 2010b). This is also well approximated by considering the circulation as being driven by subsidence induced by radiative cooling in the descending branches of the tropical circulation (e.g., Folkins et al. 2002), but may only apply to certain regions of the upper troposphere since mixing with lower-level humidity and transport from the mid-latitudes have also been shown to dominate in model simulations and reanalyses (Galewsky et al. 2005). Cloud microphysics may also modify the humidity distribution of the free-troposphere. However, modelling studies demonstrate that cloud ice plays a relatively minor role in moistening the upper troposphere compared to water vapour (John and Soden 2006). This suggests that it is inherently large-scale processes that maintain and control the relative humidity distribution at scales that are therefore resolvable by climate models simulations.

The precise dynamical controls on the "free" tropospheric humidity (above the influence of the boundary layer) require improved characterization since they may have important bearing on the overall responses of the humidity distribution (and indirectly on cloud), and hence the flows of longwave radiative energy, in a warming climate. Important in regulating these energy flows are the driest regions of the upper troposphere. Roca et al. (2012) find a dual control on one of the driest regions of the upper troposphere, located above the eastern Mediterranean: air is advected from both tropical convective regimes and mid-latitude disturbances, and the relative contribution of these two source regions exerts an appreciable affect on the relative humidity over these regions (see also Galewsky et al. 2005).

Small yet systematic changes in relative humidity in a warming climate contribute towards the magnitude of water vapour feedback and aspects of the hydrological cycle and energy flows. It has long been appreciated that a warming climate is associated with small reductions in subtropical free-tropospheric relative humidity, based upon climate model simulations (e.g., Mitchell et al. 1987; Sherwood et al. 2010a) and recent observations (Minschwaner and Dessler 2004), which reduces the magnitude of the water vapour feedback by around 5% relative to that anticipated from the Clausius Clapeyron equation alone (e.g., Soden and Held 2006). The mechanism for this change can be related to the outflow temperature of deep convection in the tropics and linked to the altitude of neutral buoyancy. This is determined by the decline in longwave radiative cooling with altitude in the upper troposphere due to reduced water vapour concentrations, again determined by the Clausius Clapeyron equation (Zelinka and Hartmann 2010). The robust physics relating to radiative transfer and Eq. 1 appears to explain positive feedback from high altitude clouds (Fig. 1) in the tropics simulated by climate models (Zelinka and Hartmann 2010; Soden and Vecchi 2011).

4 The atmospheric hydrological cycle

Near to the surface, small increases in relative humidity with warming, combined with diminishing wind stress (Gastineau and Soden 2011) and reduced near surface temperature lapse rate, appear to explain a reduced dependence of surface evaporation on temperature (2–3%/K) compared to that expected from the Clausius Clapeyron equation alone, sometimes referred to as a "muted response" (Richter and Xie 2008). Detecting the small changes in relative humidity over the oceans simulated by climate model projections is difficult. However, declines in relative humidity over moisture-limited land regions as global temperatures rise may be more apparent: projected and observed increases in land minus ocean temperature contrast (e.g., Lambert and Chiang 2007) coupled with the dominance of the oceans as a source of moisture for precipitation over land (e.g., Gimeno et al. 2010) may have contributed to recent reductions in relative humidity over land since 2000 (Simmons et al. 2010).

The present-day observed distribution of water vapour within the atmosphere is also an important diagnostic of the hydrological cycle. Substantial model biases in this distribution (John and Soden 2007) may therefore be symptomatic of inadequacies in the simulation of the global water cycle. The atmospheric hydrological cycle is intimately linked with Earth's energy flows through water vapour, from its direct impact upon the surface and atmospheric radiative budgets and also its influence on clouds and precipitation through convergence of moisture (Mitchell et al. 1987; Sherwood et al. 2010b). The radiative properties of water vapour, including continuum absorption and emission, are crucial in explaining an enhanced longwave radiative cooling of the atmosphere (Stephens and Ellis 2008; Allan

2009; Previdi 2010) and reduced radiative cooling of the surface as the climate warms. Recent advances in understanding of the links between precipitation and radiative energy budgets (e.g., Andrews et al. 2010) are discussed in detail by O'Gorman et al. (2012).

The dominance of radiative-convective processes in the tropics for maintaining temperature lapse rate (the decline in air temperature with altitude) helps to determine the increased rate of radiative cooling with increasing surface and atmospheric temperature (Lambert and Webb 2008; Allan 2009) which in turn explains why global precipitation increases with warming in the present climate at the rate of around 2–3%/K in climate models, a "muted" response relative to the increases in low-level water vapour of around 6–7%/K (Allan 2011). The differing rates of increase in water vapour and precipitation are reconciled in climate model simulations through changes in tropical circulation, in particular a reduction in the strength of the Walker circulation (Vecchi et al. 2006), although both external forcing and internally generated variability are thought to have contributed to an observed weakening over the twentieth century (Power and Kociuba 2011).

The physical basis for decreased tropical circulation can be understood in terms of the atmospheric mass flux (M) relating precipitation (P, here in units of kg/s) with low-level specific humidity (q) ignoring the small return flow of moisture at upper levels (Held and Soden 2006) (although see also Zahn and Allan 2011):

$$P \approx Mq. \tag{2}$$

Clearly, for Eq. 2 to be true, if P is constrained by the energy balance to rise at 2–3%/K and q is constrained to rise in accordance with Eq. 1 at around 6–7%/K, then M must diminish (Held and Soden 2006). Another perspective, relating to earlier discussion of radiatively driven subsidence, links vertical motion, w (km/day), to radiative cooling, Q (K/day), and the deviation from dry adiabatic lapse rate, or static stability, σ (K/km) (Knutson and Manabe 1995):

$$w = \frac{Q}{\sigma}. \tag{3}$$

In the tropics, rising temperatures are associated with a conservation of moist adiabatic lapse rate, leading to increased static stability. Therefore, the amount of subsidence required to balance Q through adiabatic heating is diminished in a warmer climate. Since the increase in stability averaged over the troposphere scales with boundary layer moisture, q, in accordance with Eq. 1 (6–7%/K), while the radiative cooling enhances at 2–3%/K, the stability changes dominate and the tropical circulation reduces (Held and Soden 2006), analogous to the situation in Eq. 2 (see also Chou and Chen 2010).

Of importance to climate impacts relating to the role of water vapour in Earth's energy flows is how precipitation and its extremes will respond to warming regionally over decadal time-scales. Locally, large-scale precipitation is dependent upon convergence of low-level moisture from surrounding regions. The Clausius–Clapeyron equation therefore provides a substantial constraint upon changes in intense precipitation events (Trenberth 2011; Sugiyama et al. 2010; Allan et al. 2010; O'Gorman and Schneider 2009; Bengtsson et al. 2009). O'Gorman and Schneider (2009) argue that the condensation rate (c) at a given level in the atmosphere associated with an extreme precipitation event scales as:

$$c = -\omega \frac{\mathrm{d}q_s}{\mathrm{d}p}\bigg|_{\theta^*}, \tag{4}$$

where θ^* is the equivalent potential temperature, denoting the change in q_s along a moist adiabat, and ω is the vertical pressure velocity in Pa/s. Assuming that almost all of the surface moisture is condensed in the storm, Eq. 4 scales with surface q_s at the rates indicated in Eq. 1. Changes in ω also strongly influence c and therefore precipitation and latent heating within storms.

The increased supply of low-level water vapour for intense rainfall is maintained in wet regions by the convergence of moisture transported from dry ocean basins of high evaporation (Gimeno et al. 2010) and may be understood in terms of the moisture balance equation (e.g., Held and Soden 2006):

$$\frac{\mathrm{d}(P-E)}{\mathrm{d}T} \approx \alpha(P-E), \tag{5}$$

where E is surface evaporation and α is equal to the terms in Eq. 1. Using this approach, Held and Soden (2006) demonstrate that Precipitation minus Evaporation ($P - E$) patterns are enhanced in a warming world. Since evaporation changes are relatively uniform, this explains why Eq. 5 is manifest most strongly as contrasting precipitation responses in the wet and dry regions of the tropics (e.g., Chou et al. 2007; Allan et al. 2010). An alternative perspective is to again consider the energy balance: latent heating through condensation of water droplets and eventual precipitation must be balanced by cooling through radiative processes and dry static energy transport, assuming other terms such as sensible heating are small (Muller and O'Gorman 2011); this may also have bearing upon the viability and stability of monsoon systems (Levermann et al. 2009).

5 Concluding remarks

While thermodynamics and radiative transfer theory provide a robust physical basis for water vapour feedback and changes in the hydrological cycle (Fig. 1), some of the details of the role of water vapour on Earth's energy flows remain to be clarified, in particular with regard to changes in the global water cycle. The Clausius Clapeyron constraint upon precipitation intensity appears to be less clear over tropical regions in models due to a varied response in updraft velocity (ω in (4)) within simulated extreme precipitation events (O'Gorman and Schneider 2009; Allan et al. 2010; Sugiyama et al. 2010) and there are substantial deviations from the anticipated 6–7%/K response in observational datasets (Lenderink and van Meijgaard 2010; Haerter et al. 2010) relating to spatial and temporal sampling scales as well as contrasting physical mechanisms such as atmospheric stabilisation or storm invigoration through intense latent heating or moisture limitation (Hardwick-Jones et al. 2010).

It is also plausible that temporary increases in the strength of the tropical circulation may yield larger precipitation responses than anticipated (e.g., Wentz et al. 2007) relative to secular trends (e.g., Semenov and Bengtsson 2002). There are also some limited observationally based analyses which suggest increases in tropical circulations (e.g., Sohn and Park 2010; Zahn and Allan 2011) although these changes may be sensitive to the assimilation of erroneous temperature lapse rate observations in the reanalyses employed (Held and Soden 2006). It is not currently clear what mechanisms drive decadal variability, nor whether the observing systems are of sufficient stability to capture such changes accurately (Trenberth 2002). A further related example relates to stratospheric water vapour which also appears to show substantial decadal variability, potentially influencing decadal temperature trends (Solomon et al. 2010), but a physical mechanism for the variation remains unclear. The characteristics of decadal fluctuations in global circulation, precipitation and upper tropospheric/lower stratospheric water vapour and their causative mechanisms currently remain an open question in relation to the role of water vapour in Earth's energy flows.

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