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Water Cycles and Climate Change

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Key information

The hydrological cycle is described. Because the climate is changing from human activities, and there is a direct effect on the hydrological cycle, water resources will also change. The effects of climate change on precipitation, evaporation, and extremes of floods and droughts are elucidated.

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Definition and Introduction

Precipitation is the general term for rainfall, snowfall, and other forms of frozen or liquid water falling from clouds. Precipitation is intermittent, and the character of the precipitation when it occurs depends greatly on temperature and the weather situation. The latter determines the storms and supply of moisture through winds and surface evaporation, and how it is gathered together to form clouds. Precipitation forms as water vapor is condensed, usually in rising air that expands and hence cools. The upward motion comes from air rising over mountains, warm air riding over cooler air (warm front), colder air pushing under warmer air (cold front), convection from local heating of the surface, and other weather and cloud systems. Precipitation is therefore also dependent on the presence of storms of one sort or another.

The water cycle varies on all time scales. Partly this arises from the inherently intermittent nature of precipitation. Of particular concern for society and the environment are the damaging heavy rains or prolonged dry spells. Hydrological extreme events are typically defined as floods and droughts. Floods are associated with extremes in rainfall (from tropical storms, thunderstorms, orographic rainfall, widespread extratropical cyclones, etc), while drought is associated with a lack of precipitation and often extreme high temperatures that contribute to drying. Floods are often fairly local and develop on short time scales, while droughts are extensive and develop over months or years. Both can be mitigated; floods by good drainage systems and drought by irrigation, for instance.

Precipitation varies from year to year and over decades, and changes in amount, intensity, frequency and type (e.g., snow vs rain) affect the environment and society. Steady moderate rains soak into the soil and benefit plants, while the same rainfall amounts in a short period of time may cause local flooding and runoff, leaving soils much drier at the end of the day. Snow may remain on the ground for some months before it melts and there is runoff. These examples highlight the fact that the characteristics of precipitation are just as vital as the amount in terms the effect on the soil moisture and stream flow.

As air warms to be above the freezing point, precipitation turns to rain. However, the water holding capacity of air increases 6 to 7% for every 1 degree Celsius increase in temperature. This comes from a well established physical law (the Clausius-Clapeyron equation). Hence, increasing atmospheric moisture occurs with a constant relative humidity because of an increase in temperature. In winter, as temperatures drop below freezing point, the air becomes “freeze dried” and at very low temperatures, below –10°C, snow tends to become very light with small flakes or even “diamond dust” like. It is only when temperatures are near freezing that huge amounts of snow fall, flakes can be large, and snow can bind together so that one can make snow-men. Similarly, as air rises into regions of lower pressure, it expands and cools, causing water vapor to condense and precipitation to form. Consequently, changes in temperature provide a very fundamental constraint on precipitation amount and type through the water vapor content of the air.

Surface moisture effectively acts as an “air conditioner”, as heat used for evaporation acts to moisten the air rather than warm it. An observed consequence of this partitioning is that summers, in particular, generally tend to be either warm and dry or cool and wet.

The long-term mean global hydrological cycle is depicted in Fig. 1 based on Trenberth et al. (2007a) who review the past estimates and provide discussion of the sources of data of the storage and flows of water through the Earth system. Several aspects remain quite uncertain, and some vary substantially from year to year and as the climate changes. Comprehensive listings of many tables of relevant data are given by Gleick (1993), who notes that “good water data are hard to come by” and that the data are “collected by individuals with differing skills, goals, and intents.”

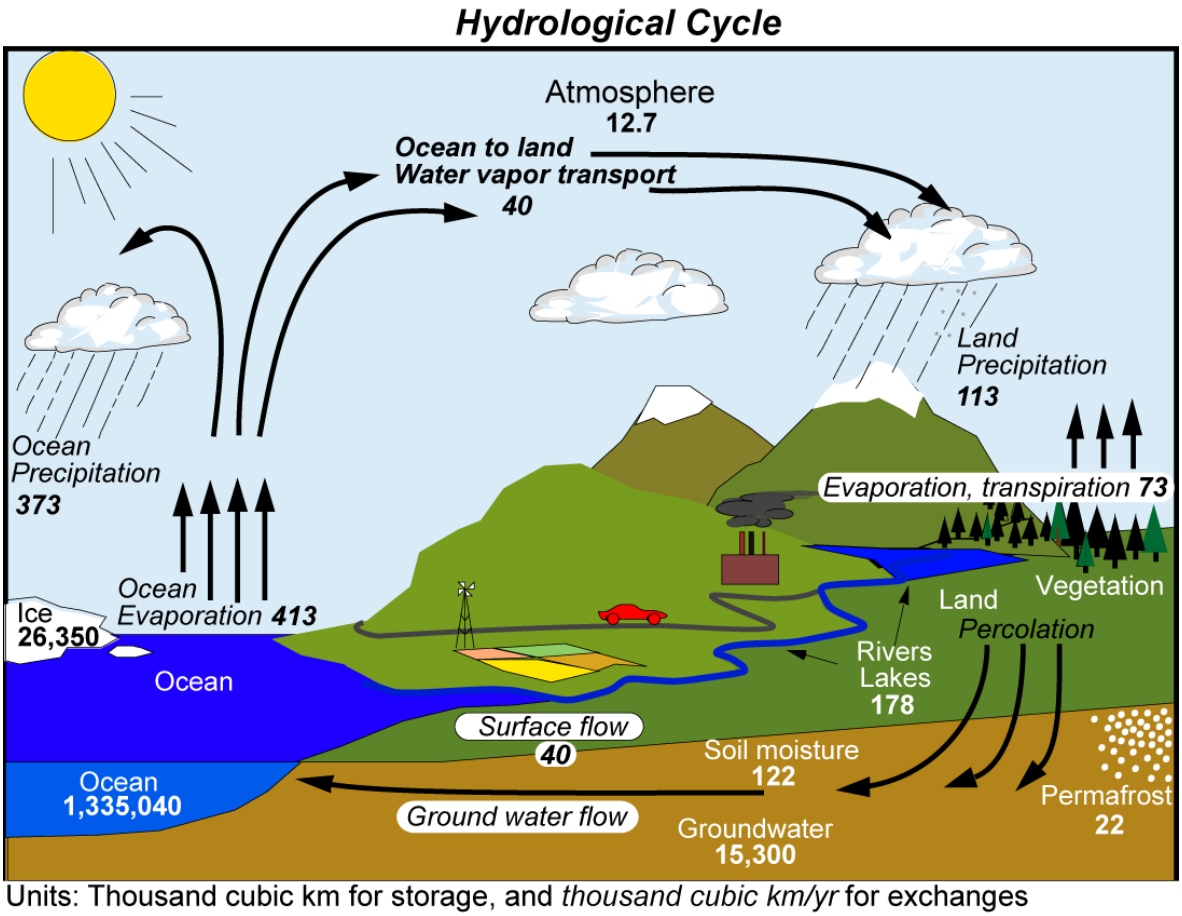

Fig. 1. The hydrological cycle. Estimates of the main water reservoirs, given in plain font in thousand (10^3) km^3, and the flow of moisture through the system, given in slant font in thousand (10^3) km^3/yr, equivalent to Exagrams (10^{18} g) per year. From Trenberth et al. (2007a).

The Role of Water in the Climate System and Climate Change

The Earth's water cycle is not only of vital interest because of the continual fresh water supply on land for humanity to exploit, but also because it plays a central role in the Earth's energy cycle and climate change. The sun's radiation enters the atmosphere and about 30% is reflected either from clouds or aerosol (particulates) in the atmosphere, or from the surface (see Trenberth et al. 2009). Some 47 to 48% of the incoming radiation at the top-of-atmosphere is absorbed at the surface and has to be balanced by cooling to maintain an equilibrium climate. It is estimated that 39% of the loss comes from net longwave radiative losses, although this involves a very large amount emitted from the surface that is compensated by down-welling radiation from greenhouse gases and clouds within the atmosphere. About 10% is lost from the surface as sensible heating of the atmosphere, for instance through thermals. The rest: about 50% is lost through evaporative cooling of the surface: moisture enters the atmosphere as water vapor to subsequently heat the atmosphere when condensed to form precipitation. Because the climate is not in equilibrium there is a small residual of 0.6% for the post 2000 period that is absorbed and serves to heat the oceans, melt ice, and cause climate change from the increasing greenhouse gases in the atmosphere owing to human activities. So the Earth is not currently in energy balance and it follows that the water cycle must also be changing as a consequence.

The term “global warming” is often used to refer to the warming of the planet from human influences and, while there are many influences, the biggest come from interference with the natural flows of energy through the climate system by changing the composition of the atmosphere and especially the greenhouse effect. Changes in aerosol cause regional variations of mixed character. Increases in certain aerosols such as sulfate particles from burning coal result in a milky whitish haze that reflects the sun and causes cooling, while carbonaceous aerosols are more likely to be absorbing and may cause local heating but at the expense of surface heating, and so both kinds can short circuit the hydrological cycle. The largest decrease recorded in global land precipitation followed in the year after the Mount Pinatubo volcanic eruption, owing to cooling from the aerosol deposited in the stratosphere (Trenberth and Dai 2007).

While one consequence of global warming is an increase in temperature, and thus the water holding capacity of the atmosphere, another consequence is an increase in evaporation over the oceans or evapotranspiration on land. Accordingly, the water cycle speeds up. For precipitation, climate models typically predict an increase in amount globally of about 2% per 1ºC warming in global mean temperature although this value is quite uncertain. Regionally this may be small or non-existent owing to aerosol effects and the best estimates of global precipitation find no trends of significance (Trenberth 2011). A robust finding in all climate models with global warming is for an increase in evapotranspiration if water is present. In the absence of precipitation, this leads to increased risk of drought, as surface drying is enhanced. It also leads to increased risk of heat waves and wildfires in association with such droughts; because once the soil moisture is depleted, all heating goes toward raising temperatures and wilting plants.

However, this is not a simple process as there are multiple downstream effects. The change in atmospheric storage is small compared with the amount cycled through the atmosphere, and thus any increase in evapotranspiration (E) is largely matched by an increase in precipitation (P) on a global basis. This also means an increase in latent heating of the atmosphere, and that deposition of heat means the vertical temperature structure of the atmosphere is affected. The immediate effect is to stabilize the atmosphere until or unless the heat can be removed by radiative processes or transported elsewhere where it may eventually be radiated to space.

The mismatch between the rate of increase in water holding capacity of 7% vs E and P of 2% per degree Celsius has other major consequences. Precipitation is inherently intermittent and on average the frequency of precipitation over the global oceans is 10.9% (Ellis et al. 2009), varying from values factors of 2 to 3 times higher at high latitudes to much lower in the subtropical regions. Over land, the average values are less and can be almost zero in deserts (see Dai 2001). Accordingly, rates of precipitation, conditional on when it does fall, are much greater than rates of evaporation, which are fairly continuous. Overall the value is probably a factor of about 10 to 25, depending on the threshold used for precipitation. It also follows that most precipitation does not come directly from local evaporation, as the mismatch in rates is so great. Nor can it come from the moisture stored in a column, which averages globally about 19 mm (January) to 22 mm (July), and varies with region so that values are over 50 mm in the tropics.

Accordingly, most moderate and heavy precipitation comes from convergence of moisture by the winds of the storm that convey the moisture from remote regions into the storm that produces the precipitation (see Trenberth et al. 2003; Trenberth 2011). Globally on average, precipitation comes from regions 3 to 5 times the radius of the rain region – or 10 to 25 times the areal value. This rule of thumb seems to apply remarkably well to many weather systems, including hurricanes (Trenberth et al. 2007b).

Hence, because precipitation comes primarily from moisture convergence, an increase in atmospheric moisture means increased intensity of events: heavier rains and also heavier snows, as is generally

observed to be happening (IPCC 2007). The rate of increase of precipitation intensity can even exceed the modest Clausius-Clapeyron rate because the additional latent heat released feeds back and invigorates the storm that causes the rain in the first place, further enhancing convergence of moisture. However, the total precipitation amount is constrained by energy availability which therefore increases at a much lower rate, and so the frequency or duration must decrease, making for longer dry spells between events in some way. This too is being observed in places where it has been examined (Groisman and Knight 2008).

Other Changes in Precipitation with Climate Change

To a first approximation, the pattern of winds do not change much with climate change, and thus the increases in water vapor guarantee that wet areas get wetter and dry areas get drier. This is referred to as "the rich get richer and the poor get poorer" change in precipitation. However, as heat is transported upwards during precipitation, with more moisture there is greater latent heat released and thus less need for the overall circulation to be as vigorous. An implication is that large-scale overturning circulations, such as the Hadley and Walker cells and monsoons, are apt to weaken. A further implication is that there must be a decrease in light and moderate rains, and/or a decrease in the frequency of rain events, as found in several studies. Thus, the prospect may be for fewer but more intense rainfall—or snowfall—events.

Other changes occur as the patterns of where storms form and tracks change, and thus the global atmospheric circulation plays a key role in the distribution of precipitation. The distribution and timing of floods and droughts is most profoundly affected by the cycle of El Niño-Southern Oscillation (ENSO) events, particularly in the tropics and over much of the mid-latitudes of Pacific-rim countries. Accordingly, small changes in sea surface temperature distributions are important in the tropics. The extremes of floods and droughts with ENSO become amplified with global warming. These aspects have enormous implications for agriculture, hydrology, and water resources, yet they have not been adequately appreciated or addressed in many studies of impacts of climate change.

In the 21st century, a robust pattern of increased precipitation polewards of about 45º is projected due to the increase in water vapor in the atmosphere and the resulting increase in vapor transport from lower latitudes. This is accompanied by decreased subtropical precipitation, although less so over Asia. Extratropical storm tracks are projected to move poleward, with consequent changes in wind, precipitation and temperature patterns, continuing the broad pattern of observed trends over the last half-century. Along with a poleward expansion of the subtropical high-pressure systems, this leads to a drying tendency in the subtropics that is especially pronounced at the higher-latitude margins of the subtropics.

The IPCC (2007) also concludes that future tropical cyclones (typhoons and hurricanes) will likely become more intense, with larger peak wind speeds and more heavy precipitation associated with ongoing increases of tropical SSTs. Because an intense tropical cyclone takes heat out of the ocean and mixes the ocean, leaving behind a much stronger cold wake than a more modest storm, there may be fewer tropical cyclones as a whole. Possible increases in stability in the atmosphere also lead to fewer tropical cyclones. Nonetheless, increased risk of flooding is a likely outcome from land-falling tropical storms.

As temperatures rise, the likelihood of precipitation falling as rain rather than snow increases, especially in autumn and spring at the beginning and end of the snow season, and in areas where temperatures are near freezing. Such changes are already observed in many places, especially over land in middle and high latitudes of the Northern Hemisphere, leading to increased rains but reduced snow-packs, and consequently diminished water resources in summer, when they are most needed. In extratropical

mountain areas, the winter snowpack forms a vital resource, not only for skiers but also as a freshwater resource in the spring and summer as the snow melts. Yet warming makes for a shorter snow season with more precipitation falling as rain rather than snow, earlier snowmelt of the snow that does exist, and greater evaporation and ablation. These factors all contribute to diminished snowpack.

It is evident that climate change has large direct impacts on the hydrological cycle and, in particular, its extremes, making managing and using water resources more challenging. Dealing with drought one year, and then floods the next, makes for major challenges for water managers on how to save in times of excess for those times when there is too little.

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