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Continental palaeohydrology and palaeoclimate during the Holocene

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Abstract

The Holocene continental hydrology, as revealed by a number of archives and proxies, fluctuates at all time scales, due to factors external or internal to the Earth system that control local, regional and global climates. Palaeohydrological reconstructions shed light on climate changes, on the history of human societies and on hydrological risk assessment. ***To cite this article: F. Gasse, C. R. Geoscience 337 (2005).***

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Résumé

Paléohydrologie continentale et paléoclimat à l'Holocène. L'hydrologie continentale à l'Holocène, enregistrée par des archives et indicateurs nombreux, fluctue à toutes échelles de temps, sous l'effet de facteurs internes ou externes au système terrestre, qui gouvernent le climat local, régional ou global. Les reconstructions paléohydrologiques éclairent les variations du climat, l'histoire des sociétés passées, et l'évaluation des risques hydrologiques. ***Pour citer cet article : F. Gasse, C. R. Geoscience 337 (2005).***

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Version française abrégée

1. Introduction

Les variations hydrologiques de l'Holocène, d'amplitude considérable comparées à celles de la période instrumentale, ont sérieusement affecté les écosystèmes, la vie humaine et les activités économiques.

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La paléohydrologie continentale vise à reconstruire le calendrier, la fréquence et l'amplitude des événements hydrologiques, l'origine et la trajectoire des masses d'eau, et à comprendre les causes et les mécanismes des changements. Ses objets – eaux souterraines, glaciers de montagne, lacs et rivières – ne représentent qu'une très faible fraction de l'hydrosphère.

2. *Variabilité hydrologique à différentes échelles de temps*

À l'échelle de 10 000 ans, les fluctuations des paramètres orbitaux de la Terre par rapport au Soleil ont joué un rôle majeur, comme en témoigne la grande période humide de l'Holocène inférieur et moyen en Afrique nord-tropicale (Fig. 1) [13,14]. Entre environ 11 et 5 ka BP (ka BP : 10^3 années avant aujourd'hui), les sociétés néolithiques évoluent dans un Sahara verdoyant, riche en lacs et cours d'eau permanents. Les aquifères se rechargent. La mousson africaine pénètre au moins 5° plus au nord qu'aujourd'hui. La circulation de mousson est renforcée par l'augmentation de l'insolation d'été sur l'hémisphère nord, induite par le cycle orbital de précession [5]. Les modèles climatiques montrent toutefois que des rétroactions positives entre insolation, températures de surface océaniques (SSTs) et végétation sont nécessaires pour rendre compte de l'amplitude des changements observés et de la rapidité du retour aux conditions arides vers 5 ka BP [8,12].

À l'échelle du millénaire, des perturbations du système climatique global non liées aux facteurs orbitaux ont brusquement modifié le cycle hydrologique, avec une expression régionale variable [23]. Ainsi, entre 9 et 8 ka BP, on recense un affaiblissement marqué des moussons africaine et indienne [13,23,24], apparemment synchrone d'un bref refroidissement centré sur 8,2 ka BP en région Nord-Atlantique [1,7,23]. Cet événement coïncide avec l'établissement des conditions hydrologiques spécifiques de l'Holocène moyen dans plusieurs régions du globe, comme l'Amérique du Sud [2] ou l'Est des États-Unis [9]. Les causes de cet événement, d'origine interne ou externe au système terrestre, sont encore débattues [23] : (*i*) la dernière grande vidange du lac glaciaire Agassiz en Amérique du Nord, freinant la circulation thermohaline océanique [3] ; (*ii*) l'augmentation des aérosols volcaniques refroidissant l'hémisphère nord [30] ; (*iii*) une diminution de l'activité solaire affectant les gradients thermiques océans–continents [24].

Par ailleurs, les grands modes de circulation atmosphérique, l'Oscillation arctique (AO), l'Oscillation nord-atlantique, *El Niño–Southern Oscillation*, qui expliquent une grande part de la variabilité climatique interannuelle actuelle, semblent avoir été modulés à plus longue échelle de temps au cours de l'Holocène. Par exemple, la variabilité millénaire de la fréquence des orages dans le Nord-Est des États-Unis (Fig. 2), dont les maxima révèlent une quasi-périodicité d'environ 3000 ans, a été associée à des changements de signe de l'AO [25], ressentis dans toute la région Nord-Atlantique [7,20,25], les périodes très orageuses correspondant à une AO généralement faible.

À plus haute fréquence, le dernier millénaire inclut le « Petit Age Glaciaire » (PAG ; • AD 1550–1850), événement climatique global de signature hydrologique régionale variable. Au centre de l'Amérique du Nord, des fluctuations centennales, sec/humide (Fig. 3), sont statistiquement corrélées avec les variations d'activité solaire, avec sécheresses aux minima d'activité solaire [29]. Inversement, ces minima correspondent à des phases humides en Afrique est-équatoriale (Fig. 4) [27]. La production biologique (diatomées) des grands lacs tropicaux tels que le Malawi (Afrique sud-tropicale) semble aussi fortement corrélée à l'activité solaire [15]. Quoique les variations d'énergie incidente soient minimes dans les derniers 1000 ans, les modèles climatiques montrent que leur effet est loin d'être négligeable [28]. Les tropiques et sub-tropiques y sont particulièrement sensibles. Les variations à l'échelle décennale des SSTs tropicales ont, de plus, engendré des changements de circulation atmosphérique et du cycle hydrologique affectant des régions extratropicales, comme l'Atlantique nord [26].

3. *Paléohydrologie continentale et sociétés humaines*

Les variations hydrologiques et certains changements socioculturels semblent étroitement liés. L'effondrement de la civilisation Maya (AD 1200–1000) [17] ou celui de l'empire Akkadien (4,2 ka BP) [11] pourraient être associés à des sécheresses régionales catastrophiques. L'histoire culturelle au Kenya paraît en accord avec la reconstruction hydrologique du lac Naivasha – prospérité/décadence en périodes humides/sèches – au cours du dernier millénaire (Fig. 4)

[27]. Les grandes sécheresses provoquent toutefois des adaptations aux conditions imposées : migration en montagne et élevage vers 9–8 ka BP en Libye [10] ; changements de pratiques alimentaires au cœur du Sahara vers 4,4–4 ka BP, lorsque la désertification proscrit la chasse et la pêche [6].

En régions arides, les aquifères profonds sont souvent l'unique ressource en eau. Il s'agit là d'eau fossile datant de périodes plus humides qu'aujourd'hui, et souvent exploitée à un taux excédant largement le taux de recharge actuel. Les eaux de fonte glaciaire, cruciales pour la consommation humaine et la production d'électricité de nombreux pays, ne sont pas éternelles non plus.

La reconstruction du passé améliore la prévision des risques hydrologiques. En particulier, l'amplitude des crues de récurrence décennale à millénaire qu'estime la paléohydrologie des rivières [21,22] aide aux décisions d'implantation d'ouvrages tels que les barrages.

4. Conclusions

La variabilité hydrologique de l'Holocène est principalement contrôlée par des changements climatiques induits par des facteurs forçant externes (paramètres orbitaux, activité solaire) ou internes (circulation thermohaline, volcanisme) au système terrestre. Elle est loin d'être comprise, malgré son importance sur les activités humaines. La paléohydrologie continentale est donc un enjeu majeur en science de l'environnement.

1. Introduction

During the past 11 500 years – the Holocene – large fluctuations in hydrology, if not in temperature, took place on the continents with spectacular amplitudes in the tropics and subtropics. Such variations have serious consequences on ecosystems, human life, and economic activities. This was recently exemplified by the August 2001 floods in Europe, or the 1970–1980s Sahel drought. Much more dramatic and persistent droughts and floods occurred before the instrumental period – the past 200 years. As the latter not only represents a small range of the Holocene variability, but was affected by human activities, it is relevant to extend to a larger scale our knowledge on natural hydrological changes.

Continental palaeohydrology focuses on (*i*) groundwater, (*ii*) mountain glaciers and permafrost, (*iii*) lake, wetland, soil and river systems (respectively 30%, 1%, and 0.3% of the land-based portion of the hydrological cycle, itself 2.5% of the hydrosphere), while polar ice, ocean and atmosphere only come up for their relations with those inland waterbodies. It reconstructs the timing, frequency, and magnitude of changes in water storage, chemistry, sources, and trajectories, and studies their causes and mechanisms.

Palaeohydrology proceeds in three steps: (*i*) primary-data acquisition from historical documents, and from indirect indicators of past conditions archived in fossil water trapped in glaciers and in aquifers, in the geomorphic prints and sediments of ancient glaciers, rivers, lakes, swamps, peat-bogs, and in cave deposits (speleothems); this is carried through satellite and field observations, sample collection, initial laboratory analyses, age measurements; (*ii*) primary-data translation into quantified parameters – calibration functions built from modern training set analysis, signal archiving intelligence –; (*iii*) process study – time-series analysis (e.g., spectral), dynamics modelling, tentative cause assignment.

2. Continental hydrological variability on various timescales

2.1. The 'orbital' timescale (10 000 years)

The smooth, long-term variations of the earth orbit played a dominant role in the Holocene hydrological variability. A striking example is the Early–Mid Holocene wetting of the northern Africa desertic belt (Fig. 1) [13,14]. From about 11 to 5 ka BP (ka BP $= 10^3$ calendar years Before Present), the Sahara was a verdant landscape with lakes and rivers, supporting large mammals and flourishing Neolithic societies. Lake Chad covered 340 000 km^2 vs 24 000 today. The Nile River received tributaries from northwestern Sudan, exoreic at that time. Aquifers were intensively recharged. Lake modelling and pollen data led to estimated increases of precipitation of impressive amplitude: e.g., $\geqslant 500$ mm yr^{-1} on northwestern Sudan, fallen today to <15 mm yr^{-1} [19]. This wetting reflects a strengthening and a penetration of the African monsoon front, related to the Intertropical Convergence Zone, at least 5–6° further north than

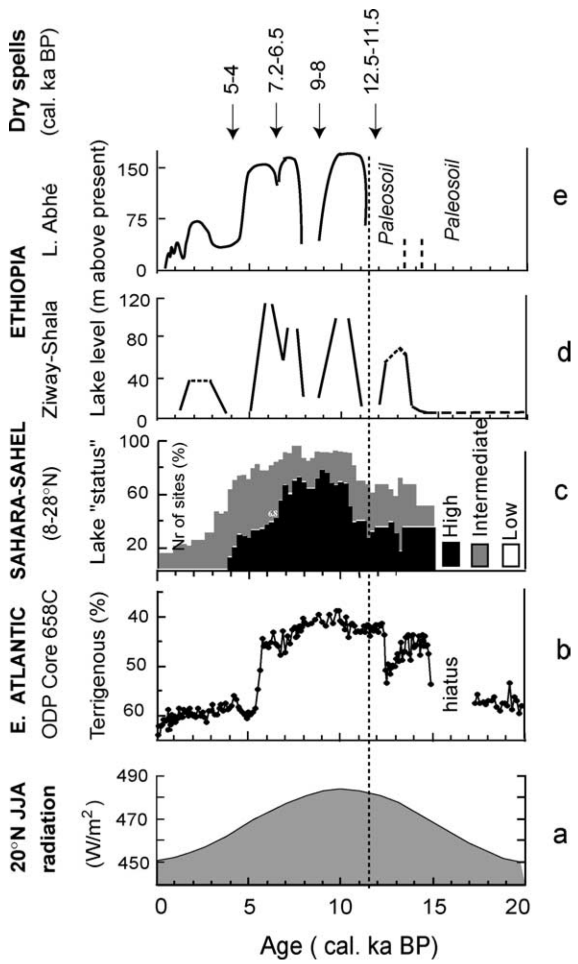

Fig. 1. The Holocene wetting of the northern desertic belt of Africa. (**a**) Summer solar radiation [5]. (**b**) Sahara dust influx off Mauritania, an index of West Africa aridity [12]. (**c**) Lake status (from 15 ka BP) in the Sahara–Sahel [18]. (**d**) Ethiopian lake-level fluctuations [13,16]. (**e**) Major Holocene droughts [13,14].

Fig. 1. La phase humide Holocène en Afrique boréale. (**a**) Radiation solaire en été [5]. (**b**) Flux de poussières éoliennes au large de la Mauritanie, un index d'aridité en Afrique de l'Ouest [12]. (**c**) État des lacs du Sahara–Sahel (de 15 ka BP) [18]. (**d**) Variations de niveau de lacs éthiopiens [13,16]. (**e**) Grandes sécheresses holocènes [13].

present-day one. Due to the orbital precession cycle (19 000–23 000 years), the northern hemisphere summer insolation was greater than today [5]; increased heating of the Sahara enhanced the ocean–land pressure gradient that drives the monsoon flow inland, and thus monsoon precipitation [8]. However, insolation forcing alone neither explains the magnitude of observed rainfall changes, nor their abruptness [8, 12,14]. General Circulation climate Models (GCMs) show that positive feedbacks with sea-surface temperatures (SSTs), soil moisture, and vegetation amplify and modify the response of the northern tropics to orbital changes [8,12].

2.2. *The millennial to centennial timescale*

2.2.1. *Globally distributed climate events*

Superimposed to orbitally induced changes, global climate disturbances generate widespread, rapid changes with different regional expressions [23].

For example, a prominent event occurred by 9–8 ka BP when the northern hemisphere was still significantly more glaciated than today. In the northern tropics, a dry spell interrupted the Early–Mid Holocene wet period (Fig. 1). Lake, pollen, and speleothem records register sag of the summer Indian and African monsoons [13,24]. In the North Atlantic region, this event is a short cooling centred at 8.2 ka BP [1,7,23], recorded as the only distinct Holocene ^{18}O shift in Greenland ice cores [1]. In many places in the world, it coincides with the onset of specific Mid-Holocene conditions, e.g., low effective moisture in the Amazon Basin and in the Altiplano [2], reduced precipitation, and increased windiness in the eastern United States [9].

Orbital variations cannot explain this large-scale abrupt event whose causes are still being debated [23]: (*i*) the outbreak of the glacial Lake Agassiz in the Laurentide at 8.2 ka BP may have abruptly slowed down the oceanic thermohaline circulation, reducing the northward heat transport [3]; (*ii*) increased volcanic aerosols in the northern hemisphere may have caused a cooling and a weakening of the Afro-Asian monsoon circulation [30]; (*iii*) the monsoon variability in Oman between 9 and 6 ka BP, as deduced from a δ^{18}O speleothem record, correlates with the tiny fluctuations of solar output regarded here as an indirect climate forcing factor [24].

2.2.2. *Changes in atmospheric modes*

Atmospheric circulation modes controlled by sea level pressure patterns, e.g., the El Nino-Southern Oscillation (ENSO), the North Atlantic Oscillation (NAO) and the Arctic Oscillation (AO), account for significant fractions of climatic variability on inter-

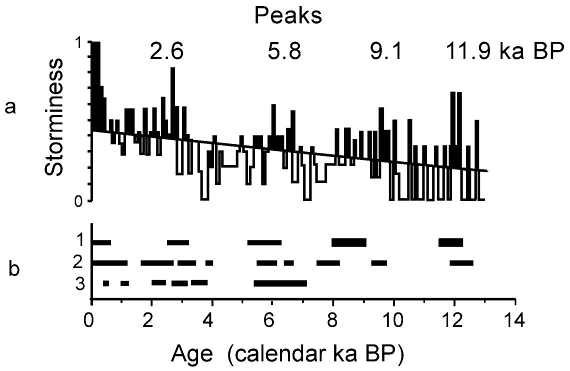

Fig. 2. Inferred storminess in the northeastern United States compared with other relevant climatic records [25]. (**a**) Histogram of terrigenous sedimentation events (100-yr bins). The trend may reflect the propagation of the stream deltas into the lakes. (**b**) Other climatic records. **1**: Greenland ice core glaciochemical cold events [23,25]. **2**: Glacial expansions in the Alps [20,23]. **3**: Periods of increased magnitude of the largest floods in the north-central United States [22].

Fig. 2. Reconstruction de la fréquence des orages dans le Nord-Est des États-Unis [25]. (**a**) Histogramme des événements à sédimentation terrigène et comparaison avec d'autres enregistrements climatiques. La tendance observée traduit la propagation des deltas des rivières dans les lacs. (**b**) Autres enregistrements. **1** : Événements froids recensés dans des carottes de glace du Groenland [23, 25]. **2** : Avancées des glaciers dans les Alpes [20,23]. **3** : Périodes d'accroissement d'amplitude des crues dans le Centre-Nord des États-Unis [22].

annual timescales. Some records suggest that such modes are modulated on longer timescales [23].

For example, the millennial-scale storminess variability in the northeastern United States has been associated with changes in the AO sign, possibly modulated by solar forcing [25]. The storm chronology (Fig. 2) was inferred from ^{14}C-dated terrigenous in-wash layers, which reflect rainfall events of exceptional intensity/duration in the 13 lake drainage basins. Maxima of terrigenous influx reveal a quasi-periodic cycle of about 3000 years. They coincide with high storminess and flooding episodes in other records from the North Atlantic area, and with cool periods in Greenland and Europe as recorded in glaciers (Fig. 2) [20,23]. Today, enhanced storm frequency in the northeastern United States is associated with the low-phase AO, when the relative strength of meridional versus zonal circulation is weak. On longer timescales, increased regional storminess likely coincided with a mode similar to the low-phase of the contemporary AO, while storm frequency was low during the high-phase AO-enhanced zonal flow [25].

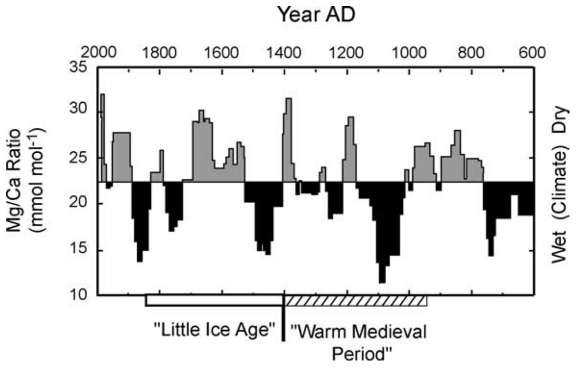

Fig. 3. Wet-dry fluctuations in central North America, inferred from the Mg/Ca ratios of ostracod shells [29].

Fig. 3. Fluctuations humide/aride au centre de l'Amérique du Nord, reconstituées à partir des rapports Mg/Ca dans des coquilles d'ostracodes [29].

2.3. *High-frequency variability*

Examples from the past millennium encompass the 'Little Ice Age' (LIA; about AD 1550–1850), well known as a cool period at mid and high northern latitudes, but now recognized as a widespread event. Again, hydrological changes occurred at a regional scale.

In central North America, drought and flood time series were produced from closed lake basins. At Rice Lake, ostracod-shell Mg/Ca ratios reveal centennial-scale wet-dry fluctuations (Fig. 3), with significant periodicities of 400, 200, 130, and 100 yr [29]. Cross-spectral analysis shows significant correlations between solar activity minima and droughts, with a 50-year lag likely due to the ocean thermal inertia [29]. Conversely, in equatorial East Africa, floods inferred from the Lake Naivasha level reconstruction coincide with LIA episodes of low solar activity, the highest level being reached during the Maunder minimum (AD 1645–1715) [27] (Fig. 4).

The biological productivity of large tropical lake ecosystems also seems related to solar forcing. At Lake Malawi, southern tropical Africa, a 700-yr diatom record reveals periodicities of about 200, 125, 100, 80–90 and 60–70 yr in the species composition and productivity that are related to the lake water balance [15] (Fig. 4). Good statistical correlations are found between Total Solar Irradiance (TSI) and di-

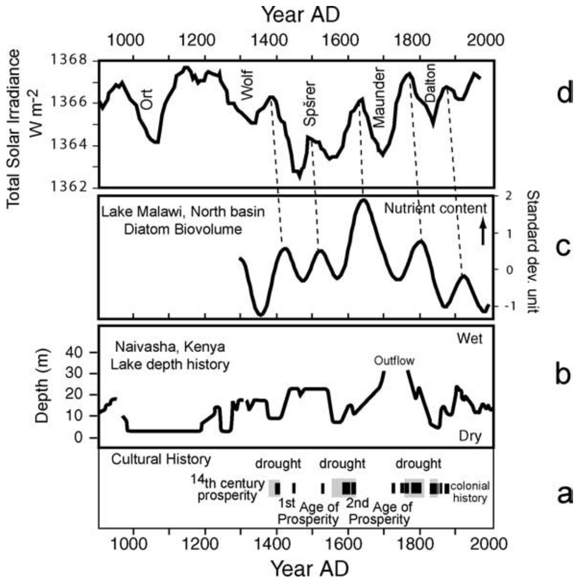

Fig. 4. Relationships between regional human cultures (**a**) [27], water-level fluctuations of Lake Naivasha (**b**), primary production (diatoms) in a large tropical lake (**c**) [15], and Total Solar Irradiance (**d**) [4].

Fig. 4. Relations entre sociétés humaines de la région (**a**) [27], fluctuations de niveau du lac Naivasha (**b**), productivité lacustre primaire (diatomées) d'un grand lac d'Afrique de l'Est (**c**) [15] et activité solaire (**d**) [4].

atom time-series. There is a time lag of a few decades between TSI and diatom production maxima/minima. The direct influence of TSI on the Malawi ecosystem is thus unlikely, but TSI oscillations can be propagated to the regional climate (e.g., precipitation) through changes in tropical SSTs.

GCMs locate the largest thermal effect of the tiny fluctuations in TSI over the tropics and subtropics, due to enhanced land-sea contrast and high tropical SST sensitivity [28]. Long-term changes in tropical SSTs also generate large-scale changes in atmospheric circulation and hydrological feedbacks, and have likely affected the AO, NAO modes, and the North Atlantic area [26].

3. Societal relevance of continental palaeohydrology

3.1. Hydrological variability and past societies

Well-dated records combining environmental, documentary and archaeological data suggest strong links between hydrological events and human cultures. For example, a major drought in Yucatan (Mexico) inferred from stable isotope ratios in lacustrine ostracods coincided with the collapse of the Mayan Civilisation at AD 1200–1000 [17]. The demise of the Akkadian civilisation at about 4.2 ka BP is associated with a major dry spell in the Middle East [11]. The 1000-year hydrological reconstruction at Lake Naivasha is in line with the regional cultural history: prosperity in the wettest LIA episodes, alternating with cultural decay during at least three severe droughts [27] (Fig. 4). However, dramatic hydrological events might have generated inventive adaptations to new socio-economic situations: in western Fezzan (Libya), game fishing and hunting became difficult in lowlands during the 9–8 ka BP drought; people moved to the neighbouring mountains, started to breed cattle and created new lithic techniques [10]. In Northern Niger, after the final desiccation of the Saharan water bodies, a food shift from meat and fish to cereals is recorded by the δ^{13}C of carbonate-hydroxylapatite in human skeletons at ca. 4.4–4 ka, likely associated with the development of agriculture [6].

3.2. Water resource implications

Exploited groundwater is 'fossil', and dates from periods of greater moisture availability, thousands of years ago. This groundwater is often mined at a rate vastly exceeding that of possible recharge under current climatic conditions, leading to swift water resource decline.

Ice-melting water is the prime water resource and hydroelectric power supply in several areas, e.g., the Andean countries of South America. The current global warming induces a rapid decay of mountain glaciers, especially in the tropics. Has such decay an equivalent in the past? This question can be approached through the study of glacier history and of dependent river and lake systems.

3.3. Hydrological risk assessment

The risk of extreme floods is of critical concern for societies, and for hydrological equipment, such as dams. Streamflow-gauging records are too short to provide realistic probabilities of heavy flow frequency distribution. Palaeoflood data, incorporated into flood-frequency analyses, extends the records [21,22]. This is exemplified by a regional Holocene flood and palaeoflood frequency study performed in northwestern Colorado [21]. The past stream regime and discharge were inferred from geomorphic and hydraulic properties of the drainage network, the channel geometry, the characteristics of channel sediments, botanic evidence, and indicators of past flood levels, e.g., slack-water or bouldery flood-bar deposits. The results help define probable maximum peak discharge in the region at recurrence intervals ranging from 10 yr to 10 000 yr [21].

4. Conclusions

Palaeohydrology finds high natural variability of inland water quality and availability during the Holocene, primarily driven by climate changes. These are linked to fluctuations in external forcing factors, e.g., orbital parameters and solar output, or internal forcing factors, e.g., oceanic thermohaline circulation or volcanic activity. There is growing evidence of the role of solar activity on hydrosystems at the millennial to decadal timescales, although clear mechanisms for such linkages are yet to be found. The atmospheric CO_2 concentration has slightly fluctuated during the Holocene, but, because water vapour is the most powerful greenhouse gas, large hydrological changes in the tropics may have had a significant effect on global climate.

The anticipated global warming is expected to cause the hydrological cycle to churn more vigorously, to increase atmosphere moisture, generate a stormier climate in some areas, drier conditions in others. But even the most sophisticated climate models do not yet provide a realistic representation of precipitation patterns at regional scales. Documenting and better understanding the basis for the full range of hydrological variability during the current interglacial period is a pressing and significant task for palaeoscience.

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