Climate regulation of humid tropical hydrology

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Abstract

The hydrology of humid tropical regions such as South-east Asia is strongly affected by climatic phenomena having important periodicities ranging from hours to decades. This paper describes how temporal climatic features influence canopy hydrology, runoff processes and water quality in the humid tropics. Emphasis is given to hydrological studies from South-east Asia, a region impacted by cyclonic, convective and stratiform rainfall, strong diurnal cycles in net radiation, and rainfall cycles resulting from monsoons and the El Niño – Southern Oscillation. Understanding how natural climate cycles affect hydrology is a necessary precursor to understanding how man-made climate changes might influence tropical water resources.

Introduction

The humid tropics can be defined as the global region covered by tropical rain forest, i.e. the broadleaf evergreen forest that covers Amazonia, much of Central America, the Caribbean, Central Africa, coastal West Africa, eastern Madagascar, south-west India, Bangladesh, and most of South-east Asia (Fosberg *et al*., 1961). Its climate contains distinctive dynamics over periods of individual storms, hours, over one to two months (e.g. Madden-Julien Oscillation), seasons (e.g., monsoons), a few years (e.g. El Niño – Southern Oscillation) and decadal time scales (Chen and Chappell, 2008). The influence of these dynamics on hydrological processes can be pronounced and is illustrated here with evidence primarily from the South-east Asian humid tropical region.

Climate impacts on canopy hydrology

Changes in the net radiation and rainfall strongly regulate the evaporation of water from vegetation canopies in SE Asia (Kumagai *et al*., 2004). Within humid tropical SE Asia, this evaporation is primarily in the form of: (a) transpiration supported by soil water, and (b) wet-canopy evaporation from rain-wetted vegetation surfaces. Wet-canopy evaporation is also known as 'interception loss'. Within humid tropical regions a significant component of this evaporated water feeds local convective cell development, which then returns water to the forest as local convective rainfall (Eltahir and Bras, 1996; Trenberth, 1998). Thus the very strong evaporation in the SE Asian region, as a result of the very high input of solar radiation (Exell, 1976), results in rainfall which is strongly convectively driven (McGregor and Nieuwolt, 1998). Such rainfall tends to be more intense in comparison to stratiform or frontal rainfall types (Bonell *et al*., 2004), which then has implications for the rate of canopy wetting, quantity of infiltration-excess overland flow, river flashiness (Robinson and Sivapalan, 1997) and sediment mobilisation. As a result, the temporal distribution of the hydroclimatic variable of evaporation is important for a range of subsequent hydrological processes. Further, changes to vegetation canopies as part of land-use change, affect evaporation and then may affect the production of locally-driven convective rainfall. GCM studies indicate that where vegetation canopy change is extensive (say greater than 10 000 km^2), then the regional climate forcing and rainfall production can be affected (Zeng *et al.*, 1999).

Diurnal variations in evaporation

The strong diurnal variation in net radiation, or energy for evaporation, strongly regulates the transpiration of SE Asian trees. This is clearly shown in studies of tree sapflow within SE Asia (Giambelluca *et al*., 2003). Higher rates of net radiation on cloud-free days give greater rates of transpiration (Kumagai *et al*., 2004; Figure 1). This correlation relates primarily to observations from the mornings, as the stomata of some trees close around midday, halting transpiration (Chappell *et al*., 2006).

With wet-canopy evaporation, the timing and amount of net radiation affects when water is evaporated from rain-wetted surfaces. Additionally, the rate of wet-canopy evaporation is strongly affected by the incidence of the rainfall which wets the canopy surfaces. After several days without rainfall, canopy is completely dry and therefore unable to lose water by wet-canopy evaporation. The very high, dense and complex canopy of the natural climax vegetation for much of SE Asia, namely rainforests, means that the spatial and temporal variations in canopy wetting is central to any understanding and prediction of wet-canopy evaporation (Bidin and Chappell, 2004). Observations of canopy wetness within rainforests are, however, very sparse (Chappell *et al.*, 2006).

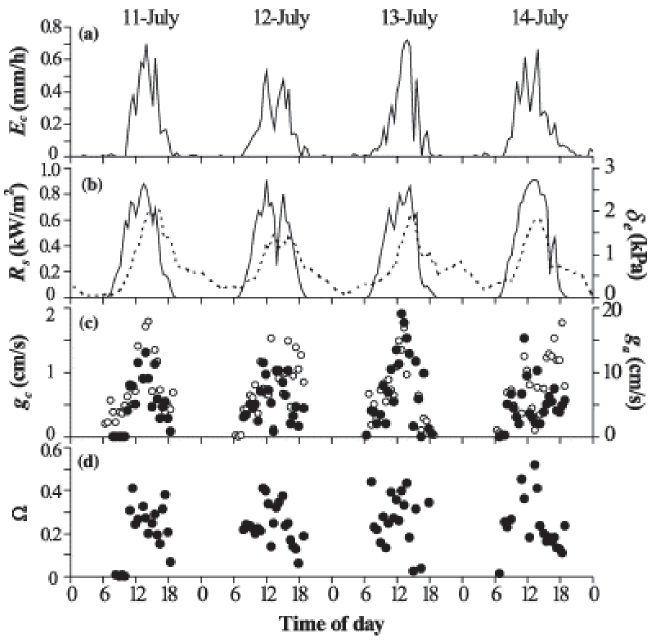

Figure 1 *Diurnal variations in (a) canopy transpiration (Ec), (b) solar radiation (Rs; solid line) and atmospheric humidity deficit (´e; dashed line), (c) canopy conductance (gc; solid circle) and aerodynamic conductance (ga; open circle), and (d) the decoupling coefficient (©; solid circle) for the period July 11–14, 2001. After Kumagai* et al. *(2004).*

Seasonal and inter-annual variations in evaporation
In seasonal parts of SE Asia (notably Indochina), extended rainless periods in the northern summer must result in very low rates of wet-canopy evaporation within these periods. Transpiration, in contrast, continues during these periods but may be reduced as soil moisture stresses develop (Tanaka *et al*., 2003). These seasonal and regional contrasts are most manifest during ENSO dry periods (El Niño periods in much of SE Asia). While rates of transpiration (and wet-canopy evaporation) reduce during these dry periods, the ratio of transpiration to riverflow may increase as the residual rainfall (i.e. precipitation minus evapotranspiration) reduces. Regional variations in the residual rainfall mean that latitudinal variations in evaporation affect the amount of riverflow entering the seas around SE Asia. GCM studies show that the spatial and temporal variations in runoff to the seas and oceans in the tropics affect the global climate (Oki *et al*., 1995).

The seasonal droughts in the northern parts of SE Asia introduce a much larger requirement for irrigation in these areas to sustain agriculture (Barker and Molle, 2004). This irrigation water use may have impacts on regional evaporation and thus cause more regulation of riverflow in the downstream parts of large watersheds (Jha and Das Gupta, 2003).

Indirect climate effects via vegetation
In the short-term, ENSO droughts affect the flowering, growth and mortality of tropical trees (Fu and Wen, 1999). These structural changes to forests affect the evaporation-rainfall-runoff linkages over the longer term. Through natural evolution, regional climate has led to the development of particular climax vegetation in SE Asia, including equatorial rainforests, seasonal rainforests, cloud forests, etc. These different forest types affect not only the canopy hydrology because of their different canopy structures (Roberts *et al*., 2004), but also the runoff processes due to differing litter depths and types (Bonell, 2004), rooting depths and densities (Roberts *et al*., 2004) and soil/rock weathering rates (Proctor, 2004).

Climate impacts on runoff processes

The routes by which water moves to streams or rivers and the shapes of river hydrographs are strongly regulated by the shape of the raingraph (or hyetograph). The raingraph can be of equal importance to the soil and rock properties in governing these runoff processes (Robinson and Sivapalan, 1997).

Storm type, intensity and non-linearity
Different storm types, notably cyclonic events, convective events and stratiform events, have different rainfall characteristics which result in different hydrological behaviour (Figure 2). In part, this is because the rainfall–runoff system is fundamentally non-linear (Chappell *et al.*, 1999), and, therefore, potentially sensitive to small changes in the rainfall characteristics.

The sustained high intensity of cyclonic events results in increased proportions of infiltration-excess overland flow during such events. Infiltration-excess overland flow occurs where the rainfall intensity exceeds the soil infiltration capacity or surface saturated hydraulic conductivity. Where infiltration-excess overland flow makes a volumetrically significant contribution to streamflow, then this water pathway can have a significant impact on the behaviour of rivers. The region's Ultisol soils have infiltration capacities of 10's or 100's cm/hr

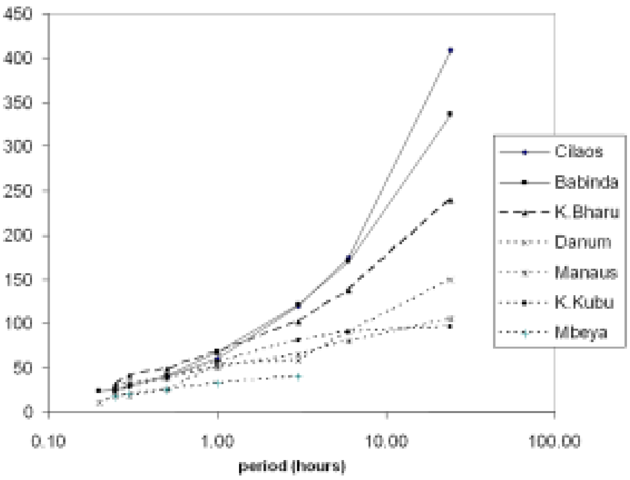

Figure 2 *Rainfall totals with a two year recurrence interval for periods up to 24 hours. Data are shown for example rainfall stations that are a) regularly subject to tropical cyclones (solid line), b) only periodically subject to tropical cyclones (broad broken line), and c) not subject to tropical cyclones (fine broken line). See Bonell et al. (2004) for the location of the rainfall stations.*

under the natural climax forest (Chappell and Sherlock, 2005) and will permit infiltration of most rainfall, even during many cyclonic events, and thus limit infiltration-excess overland flow. Where soils have been compacted or covered by agricultural, industrial or urban activities, local reductions in infiltration capacity of several orders of magnitude reduce the ground's ability to take in water, at least at local scales (Malmer and Grip, 1990). Thus the higher intensity of rainfall means that regions with a higher proportion of cyclonic rainfall events (e.g. Philippines, Myanmar, southern China, and southern Vietnam) are more sensitive to the hydrological effects of ground disturbance (see Malmer *et al*., 2004; Chappell *et al*., 2004b).

Where there is a thick organic layer on rainforest soils, then these events can rapidly saturate these layers and produce a significant volume of lateral flow within the organic horizon. This has been shown within cyclone affected watersheds in Northern Queensland, just to the south of SE Asia (Bonell, 2004).

In predominantly non-cyclonic regions of SE Asia (notably Malaysia, Singapore, Indonesia, Brunei and Timor-Leste), convective rainfall events predominate. The typically higher rainfall intensity of these events in comparison to frontal events in humid temperate environments means that streams are flashier in their behaviour (if all other environmental characteristics are the same). However, the hydrographs are expected not to fluctuate as much as those driven by cyclonic storms. Since the convective events usually last for a short time (Bidin and Chappell, 2006), stream hydrographs in non-aquifer terrain are particularly short in duration (cf. Chappell *et al*., 1999).

Effects of rainfall cyclicity

The presence of diurnal cycles in the convective rainfall of SE Asia, at least on average, means that the flow regime of SE Asian streams on non-aquifers fluctuates on a very regular basis (see e.g. Burt, 1979, for a humid temperate stream). Within the seasonal SE Asian tropics, the absence of significant rainfall in the northern summer means that streams and small rivers (with watershed areas <5000 km^2) on non-aquifers have very small or no low-flows. Similarly, during ENSO dry periods ('El Niño' years in SE Asia) the lack of rainfall reduces river low-flows in non-aquifer regions (Boochabun *et al*., 2004). Streams and rivers on major rock aquifers have significant storage volumes for past rainfall, so are insulated from the effects of short periods (months) of droughts. Similarly, large watersheds (>10 000 km^2) with extensive reservoir developments are also partly insulated from short periods of drought. The non-linearity in rainfall-runoff response means that the amplitude of the ENSO cycle in rainfall is magnified in the riverflow cycle (Chappell *et al*., 2004b), so that 'El Niño periods' have less riverflow than expected by the rainfall cycle, while 'La Nina periods' have more riverflow than expected by the rainfall cycle.

Long-term soil effects

Over the long term, the climate regulates soil development. The soils that develop under humid tropical conditions may have particular hydrological properties (Driessen and Dudal, 1991; Dudal, 2005). The predominant soil of SE Asia is the USDA Ultisol, which is equivalent to the Acrisol and Alisol groups. One important hydrological property of soils is the propensity to form natural 'soil pipes'; these features rapidly transmit water and nutrients through watersheds towards streams. There are indications that the Ultisol soil of SE Asia has a propensity to form these soil pipes (Chappell and Sherlock, 2005).

Climate impacts on water quality

The movement of nutrients, sediments and pollutants within watersheds is fundamentally controlled by the movement of water, or hydrology. Climate effects on water quantity, therefore, directly impact on water quality and a range of watershed management issues.

Leaching and export

Leaching and the export of nutrients from catchments is strongly controlled by climate. The greatest flows of nutrients along rivers are observed in periods of high rainfall input and hence riverflow generation. In SE Asia, this is seen on a within-storm basis and on a seasonal basis (Malmer, 1996). This is seen in undisturbed catchments and those disturbed by commercial forestry, shifting cultivation and agriculture. Additionally, the production of nutrients such as nitrate is also a function of solar radiation and temperature. As a consequence of the high temperature, high solar radiation and high rainfall, nutrient cycling within tropical SE Asia is very rapid (Proctor, 2004). The speed of the nutrient cycles within this region does mean that recovery following disturbance of the natural forest vegetation can be rapid in comparison to temperate areas (Malmer, 1996).

Water quality

Stream and river turbidity and sediment load are seen as key aspects of water quality in the managed rainforests of SE Asia (Chappell *et al*., 2004b). Within the undisturbed climax forests of SE Asia, extreme rainfall events account for a disproportionate amount of the long-term erosion and mass movement of the landscape that raises river sediment load. For example, the five largest storms during 1987–89, generated 45% and 54% of the suspended-sediment flux in the 19.9 km^2 Batangsi and 12.5 km^2 Chongkak watersheds, respectively, in Peninsular Malaysia (Lai, 1992). Similarly, a single storm event on the 19th January 1996 mobilised 43% of the suspended sediment flux over the period 1st July 1995 to 30th June 1996 from the 0.44 km^2 Baru catchment in East Malaysia (Chappell *et al.*, 1999). The impacts of extreme events are also observed over significantly larger space and time scales. For example, the 8-year records for the 721 km^2 Ulu Segama watershed, gauged close to the Baru catchment, show that extreme storms occurring on only six separate days (or 0.2% of the time-series) mobilised 25% of the suspended-sediment (Douglas *et al*., 1999). These larger events have these disproportionate and non-linear impacts because they (i) trigger new mass movements along channels and on slopes, (ii) markedly expand the contributory-areas of sediments mobilised by surface erosion, and mobilise channel-bed sediments (Chappell *et al*., 2004ab). This non-linearity is also seen with the magnification of the amplitude of the ENSO cycle when comparing sediment load with riverflow (Chappell *et al*., 2004b). 'El Niño periods' have less sediment load than expected by the riverflow cycle (and much less than expected by the rainfall cycle), while 'La Nina periods' have considerably more sediment load than expected from the riverflow cycle (Figure 3). These effects are particularly important for predicting the impacts of land-use change on hydrology, as the magnification effect on the ENSO rainfall signal means that forest and soil disturbance during an 'El Niño period'

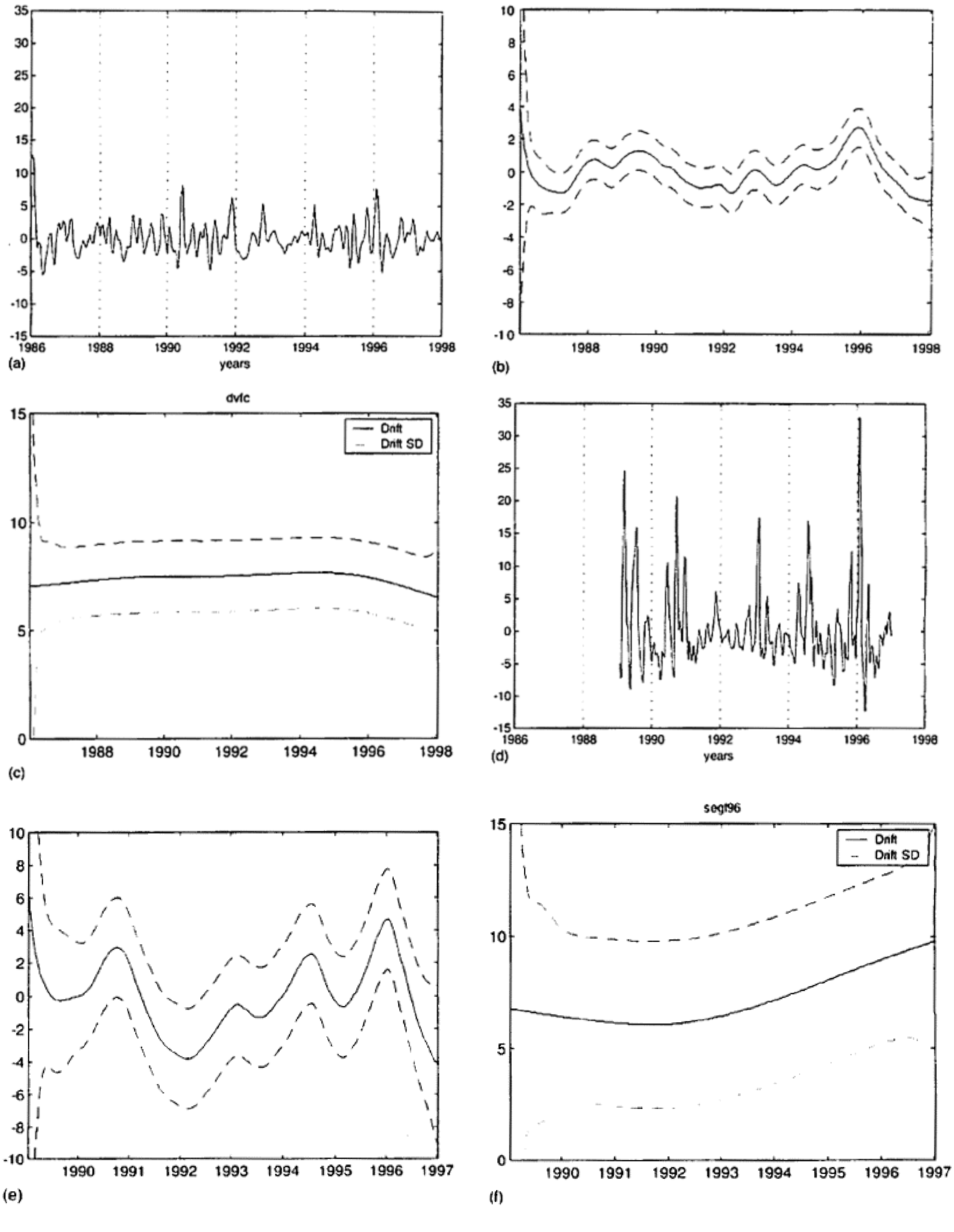

Figure 3 *Results of the Dynamic Harmonic Regression (DHR) modelling of rainfall and sediment trend and cycles in the Ulu Segama region of Sabah, Malaysia: (a) Seasonal cyclicity in the daily rainfalls (mm d^{-1}) at the Danum Valley Field Centre (DVFC) meteorological station, Sabah, Malaysia. (b) Inter-annual cyclicity in the DVFC rainfall (mm d^{-1}), (c) Inter-annual drift in the DVFC rainfall (mm d^{-1}), (d) Seasonal cyclicity in the daily flux of suspended-sediment (in mm d-1 rainfall equivalents) generated by the 721 km2 Ulu Segama catchment, (e) Inter-annual cyclicity in the daily flux of suspended sediment (in mm d^{-1} rainfall equivalents), and (f) Inter-annual drift in the daily flux of suspended-sediment (in mm d^{-1} rainfall equivalents). Adapted from Chappell et al. (2004b).*

has a very small impact on the sediment system, while disturbance during a 'La Nina period' has a very marked effect (Chappell *et al*., 2004b).

Conclusions

Climate is the key controlling factor of the regional hydrological cycle and land-surface hydrology. Within South-east Asia, storm characteristics and natural cycles within rainfall and solar radiation can be shown to exert a strong influence on the evaporation from the region's natural and disturbed vegetation covers. Of equal importance is the effect of storm-based and longer-term climatic dynamics on the pathways of rainfall towards rivers and the consequent impact on the rates and patterns of nutrient and sediment delivery to rivers.

Manmade climate change affects people primarily via changes to the hydrological phenomena of floods and droughts (Stern, 2007). To properly understand and forecast such hydrological change, we must first understand the ways that climate naturally regulates hydrology. Consequently, the increasing number of studies addressing climate change impacts on hydrology within the densely populated humid tropics should be paralleled with a more systematic quantification of the way that natural cycles and short-term characteristics of climate regulate hydrological phenomena.

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