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Climate regulation of Southeast Asian hydrology

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INTRODUCTION

The Southeast Asian tropics extends from 23.5° North (Tropic of Cancer) to 11° South, and 90-140° East, and includes the countries of Brunei Darussalam, Cambodia, Indonesia, Laos, Malaysia, Myanmar, the Philippines, Singapore, Thailand, Timor-Leste and Vietnam. Southern China, notably the regions of Hong Kong, Guangdong, Guangxi, Hainan and Taiwan extend below the Tropic of Cancer at 106-122° East and are, therefore, climatologically part of the region. The region is also known as the ‘Maritime Continent’ because of its high proportion of sea, and the ‘Warm Pool’ because of its elevated sea-surface temperatures and consequent impact on evaporation and water vapour input to the upper troposphere (Newell and Gould-Stewart, 1981; Chen and Houze, 1997b). The high water vapour input to the upper troposphere makes SE Asia important for the global climate system (Neale and Slingo, 2003) and hence the global water cycle.

The region exhibits climatic phenomena having important periodicities ranging from hours to decades (Nesbitt and Zipser, 2003; Franks and Kuczera, 2002). The strength and timing of these cycles and trends vary significantly over the latitudinal gradients from the equatorial zone to the Tropic of Cancer in the North and Lesser Sunda Islands (Nusa Tenggara) region to the South (Kripalani and Kulkarni, 1997). The spatial and temporal variability in the climatic cycles strongly affects the patterns in hydrology across the region. As a result, there are marked variations in the likelihood of flooding and droughts, the intensity of erosion and nutrient cycling, and the demand for irrigation water and water supplies. Further, the magnitudes of land-use change impacts on hydrology are also either - masked (Chappell and Tych, 2003) or regulated (Chappell *et al.*, 2004b) by the region’s climate dynamics. This chapter aims to review influential and recent studies from SE Asia that show how hydrology is regulated by climate.

CLIMATE DYNAMICS

The climatic variables that most strongly affect the hydrology of SE Asia are the precipitation and net radiation. The delivery of precipitation to the land surface is dependent on the type of storm event (e.g., cyclonic, convective, stratiform, orographic, and frontal types) and the presence of cycles on diurnal, 30-60 day Madden-Julien Oscillation (MJO), monsoonal, 4-5 year El Niño – Southern Oscillation (ENSO), and decadal time scales.

Storm type and intensity

The different types of storm event seen within SE Asia have different spatial characteristics and contrasting intensity-duration properties. Between June and November the Philippines receives a significant proportion of its rainfall in cyclonic events (Rogers *et al.*, 2000). Other SE Asian regions significantly affected by cyclones are southern Vietnam, Myanmar and southern China (Hong Kong, Guangdong, Guangxi, Hainan and Taiwan). These cyclones are formed when four conditions are present:

- the ocean must be at least 26.5 °C,
- the local atmosphere must cool quickly with height,
- it must be further than approximately 500 kilometres from the equator as it needs the Coriolis Force; and
- a high pressure area in the upper atmosphere must be present.

In contrast to the non-cyclonic rainfall events experienced throughout the majority of land areas in SE Asia, these cyclonic events have very high rainfall intensities. Bonell *et al.* (2004) report intensities of 13-40 mm per 6 minutes with a return period of two years in cyclone prone areas. These tropical cyclones can be 200,000 to 700,000 km^2 in area.

In predominantly non-cyclonic regions of SE Asia, rainfall is generated by convective cells. The high input of solar radiation in the tropical SE Asia gives rise to high rates of evaporation (‘latent heat flux’) producing local cells of convective rainfall. These cells can give rise to highly variable, if organised, rainfall at sub-kilometre length scales (Bidin and Chappell, 2003), but can also produce ‘meso-scale convective systems’ (MCSs) organised over 1,000 km length scales (Chen and Houze, 1997a). These convective events typically have rainfall intensities greater than those of stratiform or frontal events (Bidin and Chappell, 2006), but less than those of cyclonic events (Bonell *et al.*, 2004). The presence of stratiform rainfall-events in the tropics has been largely ignored; however, Houze (1977), Cifelli and Rutledge (1994) and Hong *et al.* (1999)

show that such events do occur. There remains, however, very limited data available on the short-term characteristics of humid tropical storms (Manton and Bonell, 1993; Bonell *et al*., 2004).

Cycles

Diurnal cycles

Over inland areas, the presence of a strong diurnal cycle in precipitation is largely related to the diurnal cycle in net radiation which drives the evapotranspiration which feeds local convective rainfall. As a result, precipitation over inland areas peaks in the mid afternoon (Ramage, 1964; Satomura, 2000; Chappell *et al*., 2001; Sorooshian *et al*., 2002; Nesbitt and Zipser, 2003). Coastal areas tend to have a night or early morning precipitation maximum (Ohsawa *et al*., 2001). This is because radiative cooling occurs aloft while the ocean maintains temperatures near the surface (Nieuwolt, 1981). However, it should be noted that these simple uni-modal cycles break down in some seasons or periods of the ENSO cycle (Oki and Musiake, 1994; Bidin and Chappell, 2006). Global Circulation Model (GCM) prediction of these cycles currently has only limited success (Lin *et al*., 2000; Neale and Slingo, 2003).

MJO cycles

The Madden-Julian Oscillation (MJO) is the main intra-annual fluctuation in climate in the tropics, and is most pronounced in SE Asia. It is characterised by an eastward propagating zonal circulation with a 30-60 day cycle. The MJO influences regional convection and controls the strength and position of the tropical heat source and is, therefore, an important control on the break phases of the Southwest and Northeast monsoons and ENSO. Convection is suppressed during active phases and enhanced during break phases of the MJO (Sui and Lau, 1992).

Monsoon and annual cycles

The most pronounced cycle in the climate of seasonal and equatorial SE Asia is the annual cycle related to the monsoon reversal in winds. Three major factors account for the existence of the monsoons:

- the differential seasonal heating of the land-surface due to the solar cycle which produces a pressure gradient,
- a warmer land surface promotes convection enhancing the land-ocean pressure difference; and
- the Coriolis effect causes air to flow in a curved path and change direction on crossing the equator (McGregor and Nieuwolt, 1998).

In the seasonal northern or continental part of SE Asia, the Summer or Southwest Monsoon brings most rainfall and begins in May to June, depending on latitude. In part, this is because Southeast trade winds in the Pacific collect moisture and become unstable over maritime SE Asia and then deposit rainfall over the South of the Continental SE Asia. The main Southwest Monsoon air mass affecting continental SE Asia does, however, originate in the Indian Ocean. While this air mass is weaker than that of the Northeast Monsoon, it is much deeper (up to 9,000 m along the Myanmar coast) and much more unstable (McGregor and Nieuwolt, 1998; Nieuwolt, 1981). In late September and October, the Asian continent begins to cool down, which weakens the Southwest Monsoon.

Cyclones have a greater frequency and intensity over the Philippines and the Philippine Sea than any other region in the Pacific (Rogers *et al.*, 2000). These cyclones are experienced from June to November although peak frequency is in September and October, when the surrounding oceans are at their warmest.

QBO

The Quasi-Biennial Oscillation (QBO) is a cyclical variation in the direction of tropical lower stratospheric winds. As the name suggests, there is an approximate 2-year periodicity to the cycle. In many parts of SE Asia, the QBO is of equal importance to the El Niño Southern Oscillation (Zerefos *et al*., 1992; Giorgetta *et al*., 1999).

ENSO cycles

The El Niño - Southern Oscillation (ENSO) is a climate cycle with a periodicity of 4-5 years. It includes an oceanic component (El Niño) and an atmospheric component (Southern Oscillation). ENSO is associated with variations in the Walker Circulation, the main zonal component of the tropical circulation. Under normal conditions, winds off the South American coast drive ocean currents westward, promoting up-welling of cold water along the Peruvian coast. This creates temperature and water-level gradients across the Pacific ocean with higher values in the West. The cold water in the East Pacific stabilises the air and inhibits convection and consequently strengthens the trade winds across the Pacific. These winds obtain heat and moisture as they cross the ocean before they rise in the Warm Pool region at or near SE Asia. During an ENSO event, either warm-phase El Niño or cold phase La Niña, this pressure gradient reverses and breaks the easterly air flow driving the ocean currents; consequently the ocean upwelling near the Peruvian coast ceases. The temperature gradient across the Pacific is greatly reduced which weakens and in effect reverses the Walker Cell as the zone of convection is shifted towards the centre of the Pacific Ocean and is replaced over the Warm Pool region by a zone of descent. An ENSO event is typically defined as ± 0.4 ^{o}C anomaly of at least 6 months in the Sea Surface Temperature (SST) over the 'Niño 3.4 region', namely 190-240^{o} East and 5^{o} North to 5^{o} South (Trenberth, 1997; Kang *et al*., 2002).

Decadal cycles and trends

Decadal changes in the rainfall totals over SE Asia can be observed (Krishnan and Sugi,. 2003), although the mechanism and its relationship with the ENSO remains unclear (Vimont, 2005).

IMPACTS ON CANOPY HYDROLOGY, VEGETATION AND EVPORATION

Changes in the net radiation and rainfall strongly regulate the evaporation of water from vegetation canopies in SE Asia (Asdak *et al*., 1998; Giambelluca, *et al*., 2003; Kumagai *et al*., 2004; Chappell *et al*., 2006). 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; Bidin and Chappell, 2006), which then has implications for the rate of canopy wetting (Calder, 1996), quantity of infiltration-excess overland flow (Van der Plas and Bruijnzeel, 1993), river flashiness (Robinson and Sivapalan, 1997) and sediment mobilisation (van Dijk *et al*., 2005). 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 (Becker, 1996; Eschenbach *et al*., 1998; Cienciala *et al*., 2000; Giambelluca *et al*., 2003; Kumagai *et al*., 2004). 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).

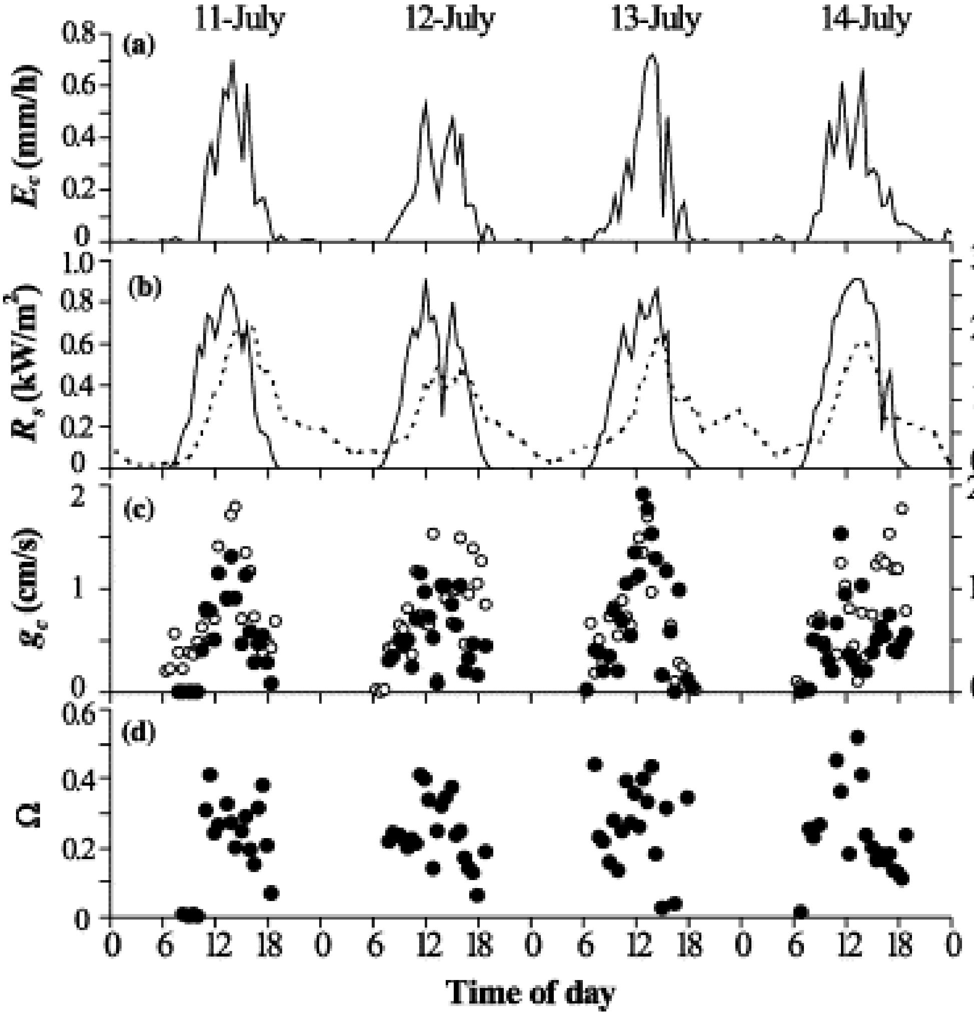
With wet-canopy evaporation, the timing and amount of net radiation affects when water is evaporated from rain-wetted surfaces. Additionally, the rate of wet-canopy evaporation is strongly affected by the incidence of the rainfall which wets the canopy surfaces. After several days without rainfall, canopy is completely dry and therefore unable to loose water by wet-canopy evaporation. The very high, dense and complex canopy of the natural climax vegetation for much of SE Asia, namely rainforests (Asdak *et al*., 1998; Bidin and Chappell, 2004), means that the spatial and temporal variations in canopy wetting is central to any understanding and prediction of wet-canopy evaporation (Federer *et al*., 2003; Bidin and Chappell, 2004). Observations of canopy wetness within rainforests are, however, very sparse (Aguilar, 2005; Chappell *et al*., 2006).

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 (Giambelluca *et al*., 2003; 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*., 1995ab).

The seasonal droughts in the northern parts of SE Asia (Laos, Myanmar, Thailand, and Vietnam) introduce a much larger requirement for irrigation in these areas to sustain agriculture (Barker and Molle, 2004).

Figure 5.1.1. Diurnal variations in (a) canopy transpiration (Ec), (b) solar radiation (Rs; solid line) and atmospheric humidity deficit (δe; dashed line), (c) canopy conductance (gc; solid circle) and aerodynamic conductance (ga; open circle), and (d) the decoupling coefficient (Ω; solid circle) for the period July 11–14, 2001. After Kumagai *et al.* (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 (Walsh, 1996; Fu and Wen, 1999; Chazdon *et al.*, 2005; Milesi *et al.*, 2005). 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 vegetations of 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 AND RIVER BEHAVIOUR

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. 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 (Van der Plas and Bruijnzeel, 1993; Godsey *et al*., 2004). Infiltration-excess overland flow occurs where the rainfall intensity exceeds the soil infiltration capacity or surface saturated hydraulic conductivity (Horton, 1933). 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 under the natural climax forest (Malmer and Grip, 1990; Chappell *et al*., 1998; Bonell, 2004; 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; Van der Plas and Bruijnzeel, 1993). 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 and Gilmour, 1978; 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 more flashy 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 (notably southern China and northern- Myanmar, Thailand and Vietnam), the absence of significant rainfall in the northern Summer means that streams and small rivers (with watershed areas <5,000 km^2) on non-aquifers have very small or no lowflows. Similarly, during ENSO dry periods (‘El Niño’ years) the lack of rainfall reduces river lowflows in non-aquifer regions (Boochabun *et al.*, 2004). Streams and rivers on major rock aquifers (see Struckmeier *et al.,* 2004) 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 insulted from short periods of droughts. 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). The predominant soil of SE Asia is the USDA Ultisol, which is equivalent to the Acrisol and Alisol groups (FAO-UNESCO, 1990). 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).

IMPACTS ON SOIL AND WATER QUALITY OF WATERSHEDS

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. Water quality is now seen as a central component of the discipline of hydrology.

Leaching and export

Leaching and the export of nutrients from watersheds 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 watersheds 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 (Chappell *et al*., 2004b).

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 watershed, 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 impact 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 timeseries) mobilised 25 % of the suspended-sediment (Douglas *et al*., 1999). These larger events have this 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 a*l., 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. 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' 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 key controlling factor of the regional hydrological cycle and land-surface hydrology. With Southeast 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.

There is a wealth of scientific research findings for the Southeast Asian region demonstrating these climate-hydrology linkages and this work has the potential to aid government agencies in managing adaptation to climate changes and the rapid land-use changes arising from equally rapid economic development. Understanding, quantifying and managing changes to water quality in particular is one of the major challenges facing countries within the region, and further research on the climate-hydrology system has the potential to make a significant contribution.

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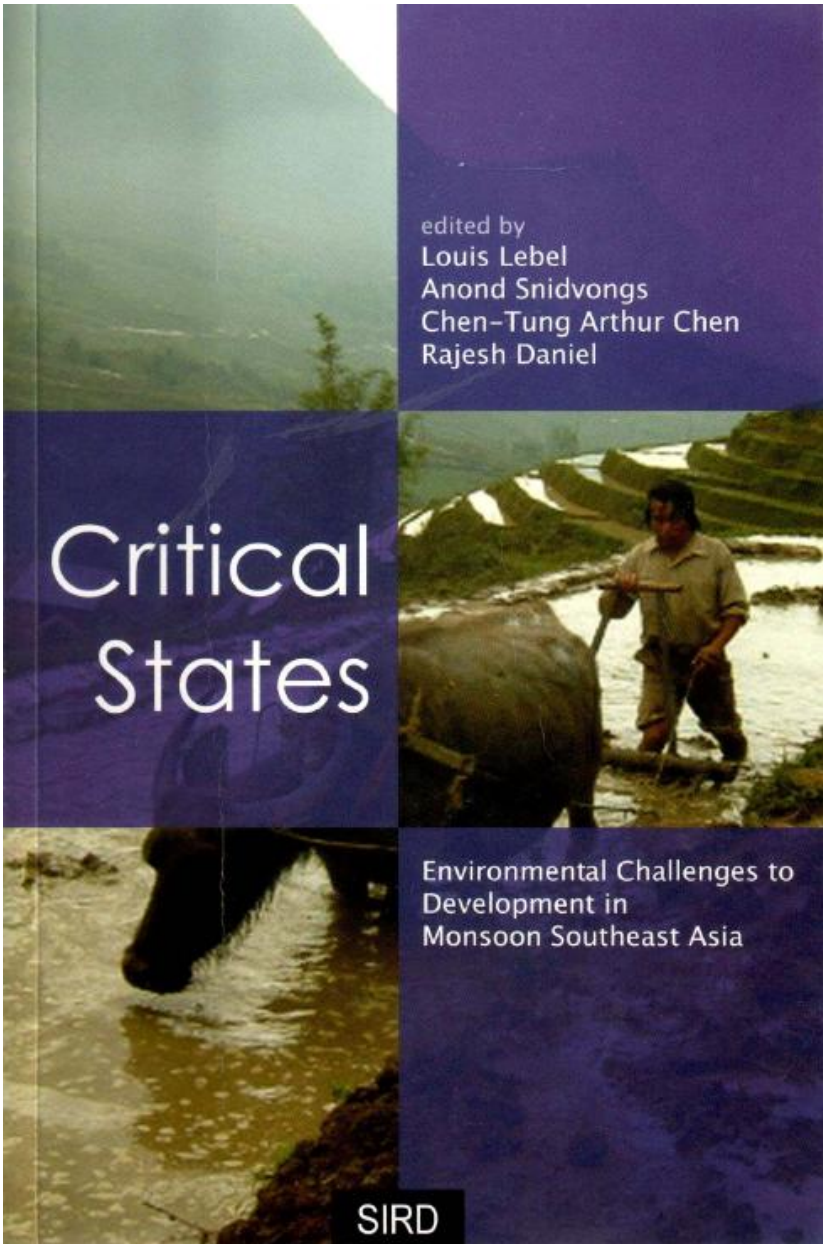

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