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Climate forcing of fluvial system development: an evolution of ideas

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Abstract

Starting from traditional ideas on the climatic steering of fluvial system dynamics, it appears that there are different kinds of climatic influences on system dynamics. They vary from direct climatic forcing (like peak precipitation) to indirect (like permafrost) and partial forcing (like vegetation). Vegetation (or its absence), and not directly climate, is considered as the main cause of fluvial incision (or deposition) during temperate (or cold) periods. However, other external factors than climate and non-climatic factors, such as local basin characteristics (like subsoil lithology and relief), express their effects on the fluvial systems by their role in the energy balance of the river catchment. Finally, internal factors in fluvial system evolution (like thresholds and response time) should not be neglected.

1. Introduction

Climate impact on the dynamics of geomorphological and sedimentological systems in general has been under discussion for some time (Vandenberghe, 2002). Therefore, it is now the right moment to evaluate the supposed steering factors, especially on fluvial system evolution. This was a central topic in symposia held in 2001 at Haarlem (The Netherlands), Nebraska (USA) and Tokyo (Japan) under the aegis of INQUA (GLOCOPH Commission), the International Fluvial Sedimentology Congress and the IGU ('Fluvial Systems' Commission) respectively.

From the three symposia mentioned above we selected a number of relevant papers that deal with the external impact on fluvial systems morphology and sedimentology at different timescales. The main focus is on climate impact, but attention is also given to the fact that this may sometimes be difficult to distinguish from other external effects, such as tectonic movements and human interference, or from internal dynamics of the fluvial system. As an introduction to this issue, this paper will put the potential impact of climate on fluvial dynamics in a historical perspective.

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2. Traditional climatic theory of fluvial development

The assignment of fluvial processes and landform development to climate impact, developed at the beginning of the 20th century in Europe. The theory of the initiator (Penck, 1910) has been considered as a reaction against Davisian theories which attributed a subordinate role to climate in landform development. Penck's approach resulted into visions of those like Büdel (1977) who developed the broader context of 'climatic geomorphology' which was popular and undisputed for many years (Table 1). The arguments used to support the preponderant impact of climate on the nature of fluvial sediments and landforms are numerous. For instance periglacial deformation structures like cryoturbations and ice-wedge casts, that occur in fluvial deposits in association with cold climate fauna caused geologists and geomorphologists to attribute fluvial sedimentation to glacial periods (e.g. Bryant, 1983; Gibbard, 1985; Seddon and Holyoak, 1985). In contrast, interglacial soils at terrace surfaces were thought to be contemporaneous with river incision between successive terraces (Sörgel, 1921). Additionally, fluvial sediments were interpreted, because of their sedimentary structures and often coarse grain size, as the remnants of braided river systems whereas meander scars at the terrace edges were considered as the traces of incising, meandering rivers operating during interglacial periods.

Table 1
Link between terrace formation and climatic periods in central Europe since about 800 kyr according to Büdel (1977)

Chronostratigraphy	Fluvial dynamics
Holocene	
Würm	Terrace formation
Eemian	
Riss	Terrace formation
Holsteinian	
Mindel	Terrace formation
Cromerian	
Günz	Terrace formation

Thus, we may wonder whether any problems remain. Staircases of fluvial terraces and equivalent deposits in many river systems seem to support their climatic origin. However, the climatic theory has been contested from the beginning. In the theory of dynamic equilibrium (Hack, 1960), and especially since the publication of the work by Leopold et al. (1964) the importance of processes in the non-cyclic development of fluvial landforms was stressed. Process approaches may even disregard completely climatic control. Later, Schumm (1977), Hey (1979) and Bull (1991) put internal dynamics and feedback mechanisms within the river system to the foreground under the concept of 'complex response'. They derived an autocyclic fluvial developmental model that operated after an initial (external) impulse (Schumm, 1979). This was controlled by thresholds that have to be exceeded before any change in landform development may take place. Thresholds could be crossed due to either internal dynamics or by external forces, such as climatic changes. Similarly, Dury (1985) tried to reconcile the concepts of fluvial equilibrium with concepts of Quaternary climate change, by giving a physical basis to the latter concepts. The physical basis of these theories was especially helpful in attempting to avoid the dangers of the interpretative, intuitive and thus often subjective, climatic geomorphology of the German (e.g. Troll, Louis, Büdel) and French school (e.g. de Martonne, Birot, Tricart). It is remarkable that the purely climatic origin of all changes in the river system, even during the Holocene (e.g. Schirmer, 1983; Starkel, 1988), was opposed even in Germany e.g. by Buch (1988) and Buch and Heine (1988, 1995).

3. Arguments opposing the traditional climatic forcing theory

Thus, in the short history of geomorphological science several theories have been developed that only partly involve climatic forcing. This is a clear indication that the role of climate in steering landform evolution might sometimes be minimal or even absent. It is interesting to investigate the roots for such a theory. Here are some examples which contradict a direct relationship between climate and fluvial system evolution:

a. The formation of terrace deposits during glacial periods, one of the fundaments of traditional concepts of climate-derived fluvial development, is contradicted by the discovery of interglacial deposits within cold terrace sediments. Illustrative examples are the temperate climate soils and faunas described in the terraces of the British rivers (Green and McGregor, 1980; Bridgland, 1994; Gibbard et al., 1996). Temperate climate life was also present towards the end of an intra-Saalian Maas terrace near Maastricht in The Netherlands (Duistermaat, 1993; van Kolfschoten, 1993) and was accompanied by soil formation of the luvisol type (Huijzer and Mücher, 1993).
b. In climatic geomorphology fluvial accumulation is supposed to be typical for glacial periods and incision for interglacial periods. However, it is remarkable that the deposits of river terraces are often quite thin relative to the total duration of the glacial period during which they are formed. Besides, it is also remarkable that during the Holocene (but before deforestation) most lowland rivers were not incising but show some equilibrium between erosion and deposition, reflecting a steady state. Nevertheless, incision remains dominant in uplifted regions throughout cold and temperate periods as long as the rivers are in an unsteady state (Vandenberghe, 1995a).
c. Furthermore, much work suggests that rivers did not only incise during temperate climates, but also within cold periods. Such cases have been described for both small (Rose and Boardman, 1983; Van Huissteden and Vandenberghe, 1988; van Huissteden, 1990; Starkel, 1994) and large valleys throughout Europe during the Last Glaciation (e.g. Huisink, 2000; references in Mol et al., 2000; Van Huissteden et al., 2001). However, a link with climate does exist as these phases of erosion usually coincide with climatic transitions during the glacial periods (Vandenberghe, 1993). At least, the relationship between climate and river incision or aggradation appears to be a complex one (Rose, 1995).
d. It appears in many cases that during the cold stages rivers changed their braided pattern, that was supposed to be typical of cold environments, into meandering or anastomosing patterns that are considered typical for temperate conditions (e.g. Van Huissteden and Vandenberghe, 1988;

Kryszkowski, 1990; Mol, 1997; Huisink, 2000). Such pattern changes may also occur during temperate periods (Gibbard and Lewin, 2002; Huisink et al., 2002).

Besides this evidence of temporal changes in specific river catchments, there is also the evidence that present-day rivers change their pattern within their own catchment without any apparent climatic change. For instance, the Usa river in Northwest Siberia both meanders and braids (Huisink et al., 2002). In northern Canada meandering rivers co-exist with braided rivers in the same region without any climatic control (Vandenberghe, 2001).

Thus, cold environments were not always characterised by braided river patterns and fluvial aggradation, while warm conditions do not necessarily initiate meandering and incising rivers. It may be concluded that, with increased knowledge of both the processes and the climatic conditions under which the landforms developed, a simple, direct, climatic explanation can not be found for many fluvial deposits and landforms. This undermines the general belief in a straightforward relation between fluvial development and climate, as has been advocated previously.

4. Climate-controlled fluvial development?

Although a direct relationship between climate and fluvial dynamics is obvious in many cases, this does not apply in all cases. Then the question arises as to how the discrepancies between fluvial activity and prevailing climatic conditions may be explained. Several reasons may be put forward. (i) Climate forcing should be specified in more detail; (ii) the role of other external controlling factors that are only indirectly or partially determined by climate should be estimated; (iii) non-climatic factors have also to be considered. The *limitations of direct impact* of climate on landform development are most obvious when looking more precisely to the governing processes. For the sake of simplicity, we are not discussing here external forcing mechanisms like the impact of human activity, tectonics or sea-level changes, nor the internal evolution within fluvial systems.

4.1. Specific climatic parameters

Main climatic parameters like mean annual temperature and annual precipitation play only a relatively minor role in determining the processes of erosion and deposition in rivers. It is well known that the *intensity* of precipitation and its seasonal distribution are much more important. Extreme events, at a recurrence interval of years or tens of years, in general leave the largest imprints in sediment production. This is apparent in the subdivision of river types in high-latitudes, which is largely determined by amplitude and duration of peak flows and not by mean temperature or precipitation (Church, 1983; Woo, 1986). It is also important in monsoonal and semi-arid conditions as is shown in the present issue by Jain and Tandon (2003).

Snow may be considered as a direct climatic forcing factor, although it is the *rapid thawing* of the snow and the role of snow (and ice) in *damming* river channels that are the most important factors in determining fluvial processes. The water that is released by snow melt contributes to the peak runoff during spring break-up (McCann et al., 1971). Snow is also preferentially deposited in river valleys and may (together with river ice) act as a barrier in the channel, diverting or prohibiting flow and thus inducing flooding ('icing') during the initial phases of break-up (e.g. Pissart, 1967). As a result, flood marks and thin sheets of often coarse-grained sediment may cover extensive areas of the floodplain.

4.2. Climate-derived factors

Relief intensity, together with discharge, determines the available energy in the system (Lane, 1955). Other catchment properties, such as soil permeability and cohesion, and surface roughness control the supply of sediment towards the fluvial system. Although these parameters are azonal, their magnitude may often be strongly determined by climate. In this way climate is an indirect steering factor.

A most striking example of such indirect steering is the occurrence of *permafrost* or seasonally frozen soils. Frozen ground reduces soil permeability for large parts of the year thus enhancing surface runoff, and concentrating it in a short period (Church, 1983; Woo, 1986). This property may also influence hillslope stability due to loss of shear strength caused by increased pore-water pressure during thaw of the active layer (Lewkowicz, 1988; Andres et al., 2001). Thus, potential sediment delivery to arctic and subarctic rivers is to a large extent determined by the presence or absence of a frozen subsoil. Periodically high-energy conditions result in the capacity of periglacial rivers to transport large amounts of coarse-grained bedload, such as found in both palaeo- and contemporary periglacial river deposits. Kasse et al. (2003) illustrate aptly the change of river style at the time continuous permafrost was established during the Weichselian Middle Pleniglacial in eastern Germany.

Another consequence of the reduced or inhibited infiltration is the near-absence of groundwater storage and thus the relatively low contribution to baseflow in the discharge of periglacial rivers (Woo and Winter, 1993). The periodic high surface runoff leads also to a

Table 2
Synthetic representation of periglacial river types as a function of vegetation, permafrost conditions and sediment supply (from Vandenberghe, 2001)

		no vegetation	patchy vegetation	continuous vegetation
permafrost (partial to continuous)	low stream power/ sedim.supply high	BRAIDED	BRAIDED → MEANDER. BRAIDED	MEANDERING ANABRANCHING
partial permafrost/ deep seasonal frost	low stream power/ sedim.supply high		MEANDERING ANABRANCHING BRAIDED	

higher stream density and thus to the extension of the hydrographic network (Kasse, 1997), an observation that also has been demonstrated by model simulations (Bogaart et al., 2003c). Such headwater channels become inactive after the melt of permafrost and are thus transformed in 'dry valleys' (e.g. Klatkowa, 1967; Vandenberghe and Woo, 2002).

4.3. Partially climate-dependant factors

Fluvial processes are also influenced by factors that are only partially climatic in origin. For instance, *vegetation cover* is a factor which is largely, but not fully, controlled by climatic conditions, and which appears as extremely important in fluvial processes (e.g. Brown, 1995; Huisink, 2000; Millar, 2000; Van Huissteden and Kasse, 2001; Huisink et al., 2002). Vegetation controls the susceptibility of surface sediments to erode by runoff, mass wasting or aeolian action and contributes to evapotranspiration. Its presence or absence is extremely important in stimulating river incision or aggradation respectively by intercepting rainfall and modifying soil infiltration capacity. For instance, in both present-day and former arctic rivers the high diversity of river patterns may (partly) be attributed to the impact of vegetation as a result of the high variability of the vegetation density and character (Vandenberghe, 2001; Vandenberghe and Woo, 2002; Table 2). Typically, fluvial deposits from cold periods are more extensive than those from temperate periods which points to a higher sediment supply at these colder periods.

Especially the *changes* in vegetation type and density induced short periods of river instability (Vandenberghe, 1993, 1995b). Both degrading and colonizing vegetation induce low evapotranspiration and thus a high runoff, but are able to protect the soils, which causes low sediment delivery to the rivers. Both situations may lead to short periods of erosion or change in fluvial style, as illustrated by Kasse et al. (2003) after the forest degradation at the end of the Eemian and during the re-vegetation at the transition from Early to Middle Pleniglacial. Also river incision that is widely recognised as taking place at the beginning of the Weichselian Lateglacial and Holocene in western Europe has been linked previously with the re-vegetation of a barren or less vegetated surface (e.g. Vandenberghe et al., 1984; Starkel, 1995; Antoine, 1997; Huisink, 2000; Mäusbacher et al., 2001) and is now confirmed by new data from Antoine et al. (2003) and Pastre et al. (2003). Thanks to precise chronology at the beginning of the Lateglacial, Antoine et al. (2003) demonstrate that this incision predates the full development to a shrub and arboreal cover, and thus is not linear with this vegetation development (Huisink, 2000).

The response of river behaviour to vegetation is, however, a complex one. For instance, precipitation effects may overrule the impact of the vegetation. Nador et al. (2003) use the rather continuous fluvial accumulation in intra-montane basins to describe the Pleistocene evolution of the river systems draining into the Pannonian basin in Hungary as a function of orbital climate evolution. They find increased sediment fluxes during the interglacials but declined fluxes during the glacial periods, and explain this phenomenon as the result of increased (resp. decreased) precipitation and transport capacity during interglacials (resp. glacials). A same hypothesis of high sedimentation rates due to increased precipitation is put forward by Rose (1984) for equatorial rivers. Jain and Tandon (2003) record similar

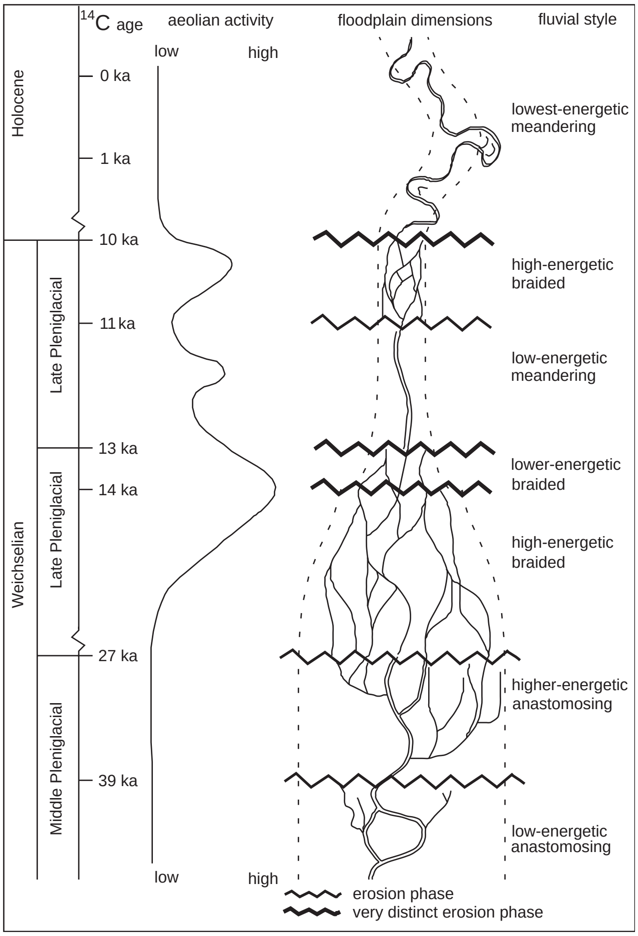

Fig. 1. Compilation of fluvial changes in the Vecht valley from the Middle Pleniglacial to the Holocene with phases of erosion and aeolian activity (adapted from Huisink, 2000).

responses of the fluvial system to Lateglacial climatic changes in the monsoonal and semi-arid conditions of western India in comparison with the temperate regions. However, more pronounced precipitation gradients and aeolian activity interplay with vegetation cover. And Bogaart et al. (2003b) require in their model simulations not only vegetation, but especially precipitation as a major input to explain the observed incision at the beginning of the Younger Dryas in the Maas valley in The Netherlands.

4.4. Non-climatic factors

Excluding the indirect tectonic controls, and taking together all direct, derived and partial climatic factors that may drive changes in fluvial processes, there are still a number of facts that cannot be explained. Two examples are given:

(i) It has been shown at many occasions that river patterns varied within both cold and temperate episodes of the Quaternary. This is a reflection of the different behaviour of rivers even when climatic conditions did not differ. For instance, in both contemporary and past periglacial regions meandering, anabranching and braided rivers or river sections may occur alongside each other (references in Vandenberghe, 2001; Vandenberghe and Woo, 2002) (Fig. 1).

(ii) Different climatic conditions may give rise to identical fluvial sedimentation and morphology. This may be illustrated with some examples from western and central Europe where typical large meanders remained unchanged during the considerable climatic changes of the Lateglacial, while braided or anastomosed systems were maintained throughout the different climatic conditions of the Last Glacial (Antoine et al., 2003; Kasse et al., 2003). As a result, each river pattern occurred throughout both cold and temperate periods.

Basin properties (like topography, valley width and subsoil lithology) may of course play a decisive role in fluvial development since they determine energy conditions within the fluvial process system or the 'accommodation space' that is available for fluvial development (Rose, 1995; Kasse, 1998; Mol et al., 2000). This is illustrated in the present issue by Houben (2003) who distinguishes between site-specific and regionally significant river responses as one of the factors that (partly) explains variable responses to climatic forcing during the Lateglacial. It is also similar to the role of the geographical position within the catchment (Rose, 1995).

Another important non-climatic element that may explain fluvial system evolution is the proximity to *threshold* values (Schumm, 1979). It has been shown, for instance, that relative coarse-grained bedload and steep longitudinal gradients stimulate the abrupt transformation to river braiding of the Younger Dryas Maas river in The Netherlands (Vandenberghe et al., 1994) and the Holocene Usa river in north Siberia (Huisink et al., 2002). In contrast to the well-established climatic changes of the last deglaciation, the rapid climatic oscillations that are present in marine and ice records of the preceding Pleniglacial period are not easily detected in terrestrial environments, and it is even more difficult to identify the potential effects of such oscillations on fluvial systems. Kasse et al. (2003) discuss this problem by means of a well-documented fluvial record in eastern Germany. They attribute a major role to thresholds in both the fluvial and climatic systems for a possible response of the rivers to these climatic oscillations. On the contrary, Pastre et al. (2003) stress, with new data, that the absence of vegetation or geomorphological thresholds generally prevented changes in the Lateglacial Seine system in France. Although the changes in that fluvial system are very comparable with those in other regions of western and central Europe, the role of thresholds in partially climate-dependant factors like soil formation, vegetation and aeolian sand supply is well illustrated.

Furthermore, it has been shown that fluvial systems need *time to respond* to changing external conditions (Schumm, 1977; Bull, 1991). This means that the duration of climatic oscillations must be long enough to allow a particular system to react to the forcing process (Van Huissteden et al., 2001; van Huissteden and Kasse, 2001; Vandenberghe and Maddy, 2001). Although the duration of such climatic events need to be longer to affect large catchments in comparison with small ones, the relatively small catchments are most sensitive to illustrate the effects of response time as shown, for instance, by the reconstructions by Pastre et al. (2003) and Kasse et al. (2003), while models simulate an adaptation time in the range of 500–1000 years for the middle Maas reach (Bogaart et al., 2003b).

Although tectonic and anthropogenic influences are not dealt with in detail in this issue, a few papers highlight the difficulties of disentangling these factors and climatic forcing. Uribelarrea et al. (2003) use historical documents to differentiate floodplain development (river flooding and channel abandonment) in Central Spain according to potential forcing factors (rainfall and human intervention) and internal dynamics. Tectonic movement, as another forcing factor that may interfere with climatic control, is discussed in general terms by Starkel (2003). He gives a series of criteria that should help to separate climatic from tectonic control, and illustrates them with a number of examples from regions with different tectonic uplift. In a specific case, Timar (2003) distinguishes between tectonic movements, affecting the river's longitudinal gradient, and sediment load in the river (as a partially climate-dependant factor) as controlling factors of the channel sinuosity of the Tisza river in the Pannonian basin.

5. Some new tools in the study of fluvial development

A main problem in estimating fluvial activity is the age control of erosional phases. These are mostly dated by adherence to the ages of the previous and subsequent deposits. For some high-energetic rivers and for recent timescales a solution may be found in lichenometry (Gob et al., 2003). Lichenometry of the large blocks in the river bed provides a promising method of reconstructing not only the recurrence period of large floods, but also an estimate of their strength. Likewise, river incision may be dated from the lichens on fresh, erosional valley sides.

Two already mentioned papers of Bogaart et al. (2003a, b) present another methodological study. These authors developed a process-based numerical model to simulate the river's response to rapid climate changes. The model is especially intended to carry out sensitivity analyses of the effects of different external climatic, climate-derived or partially climatic factors on catchment hydrology and dynamics of sediment transport in alluvial river systems. Predictions are made for discharge, channel sediment transport, channel pattern and incision potential, and are compared with geomorphological observations. Climate data are derived from geological reconstructions and atmospheric circulation models.

6. Conclusion

All these facts and restrictions may leave us uncomfortably with our original question about the significance of climate for fluvial geomorphology and geology. But, the contributions in this issue show finally that there is not one unique relationship, but a rich diversity of climate-related factors that control fluvial development.

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