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Article (refereed)

Dadson, Simon J. 2010 Geomorphology and earth system science. *Progress in Physical Geography*, 34 (3). 385-398. 10.1177/0309133310365031

1 **GEOMORPHOLOGY AND EARTH SYSTEM SCIENCE**

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5

6 **Abstract**

7 Earth system science is an approach to obtain a scientific understanding of the entire Earth system

8 on a global scale by describing how its component parts and their interactions have evolved, how

9 they function, and how they may be expected to continue to evolve on all time-scales. The aim of

10 this review is to introduce some key examples showing the role of earth surface processes, the

11 traditional subject of geomorphology, within the interacting Earth system. The paper considers three

12 examples of environmental systems in which geomorphology plays a key role: (i) links between

13 topography, tectonics, and atmospheric circulation; (ii) links between geomorphic processes and

14 biogeochemical cycles; and (iii) links between biological processes and the earth's surface. Key

15 research needs are discussed, including the requirement for better opportunities for interdisciplinary

16 collaboration, clearer mathematical frameworks for earth system models, and more sophisticated

17 interaction between natural and social scientists.

18

19 **1. Introduction**

20 On May 12th 2009, the United States National Aeronautical and Space Adminstration (NASA)

21 issued a press release which began as follows: "Twenty years ago NASA embarked on a

22 revolutionary new mission for its Earth science program: to study our home planet from space as an

23 inter-related whole, rather than as individual parts." (NASA, 2009). Few would doubt the

24 revolutionary impact of this "mission", and of the concomitant allocation of the US national science

25 budget to Earth Sciences. As NASA themselves went on to claim that their: "…vision laid the

26 groundwork for advances in global climate change and understanding natural and human-induced

27 changes in the land surface, atmosphere, oceans, biosphere and Earth's interior that affect all aspects

28 of life.”

29

30 The emergence of Earth Systems Science is therefore closely linked with the development of space-

31 borne sensors for monitoring the Earth System at global and regional scales. Since it is information

32 from the earth's surface which the satellite sensors receive, the role of geomorphology in Earth

33 Systems Science had the potential to be huge, both as the object of direct investigation, and as a

34 surrogate for processes that operate in the zone where the biosphere, hydrosphere, atmosphere and

35 lithosphere interact. Another key technical advance, which was to provide a crucial dataset showing

36 the link between the biosphere and the atmosphere, was provided by Keeling's (1960) installation

37 of infra-red gas analysers at locations in Antarctica, Hawaii, and California. Prior to Keeling's

38 observations, it was believed that fluctuations in atmospheric carbon dioxide contained no

39 systematic trend. By carefully isolating the influence of volcanic emissions and locally-emitted

40 CO_2, Keeling (1960) revealed two key aspects of the coupled atmosphere-biosphere. The most

41 celebrated finding was a secular increase in carbon dioxide concentrations which is attributed to a

42 combination of fossil fuel combustion and changes in land-use (Keeling, 1960), and which has been

43 monitored continually at many locations over the 50 years since. The second of Keeling's findings

44 concerned the natural seasonal cycle of atmospheric CO_2 concentration, in which higher rates of

45 plant photosynthesis during the boreal summer lead to a relative decrease in globally-averaged

46 concentration of atmospheric CO_2 during this period. Taken together, these findings were among

47 the first to combine precise measurements of earth system properties, with the concept of

48 meaningful interactions between the biosphere and the atmosphere. These links occur through

49 variations in earth surface properties, placing geomorphology in a key position to contribute to the

50 wider debate. The aims of the present review are therefore to describe some of the contributions that

51 Earth System Science has made to geomorphology, to evaluate some of the contributions that

52   geomorphology has made to Earth System Science, and to suggest some key areas of Earth System

53   Science to which geomorphology can contribute in the future.

54

55   **2. What is Earth System Science?**

56   The first widely-cited use of the term Earth System Science is in a report written for NASA in 1988

57   by Francis Bretherton, entitled *Earth System Science: A Closer View.* This report set out a goal for

58   Earth System Science: "to obtain a scientific understanding of the entire Earth system on a global

59   scale by describing how its component parts and their interactions have evolved, how they function,

60   and how they may be expected to continue to evolve on all timescales." (Bretherton, 1988, p. 11).

61   Moreover, the report recognizes a new challenge to: "develop the capability to predict those

62   changes that will occur in the next decade to century, both naturally and in response to human

63   activity" (p. 11).

64

65   Whilst acknowledging that "Global connections among the Earth's components began to be

66   recognizes in the last [i.e., 19th] century" (p.25), and pointing specifically to the contributions of

67   Hutton, Lyell and Darwin, Bretherton's (1988) report passes only briefly over the intellectual

68   history of Earth Systems Science insofar as it is connected to (physical) geography. As Richards

69   and Clifford (2008) point out, it is: "in NASA's interests to promulgate a totalizing view of ESS,

70   since its mission is Earth Observation" (p. 1325). Bretherton's proposed methodology is that: "By

71   examining our present knowledge of [these] processes and phenomena we can identify what are

72   probably the most significant interactions among them, quantify that understanding in terms of

73   explicit models, and devise observations and experiments that test many of the important

74   conclusions." (p. 26).

75

76   Since the publication of NASA's manifesto, several other groups have discussed the relevance of

77   Earth System Science and the integration of geomorphology within its remit (Church, 1998; NERC,

78   2007). Paola *et al.* (2006) positioned their vision of a "predictive science of Earth surface

79   dynamics" in the context of a series of integrating challenges (p.1), noting that pursuit of these aims

80   required collaboration between hydrologists, geomorphologists, ocean and atmospheric scientists,

81   sedimentary and structural geologists, geochemists, and ecologists. They call for: "…the scientific

82   community to work together towards this grand goal [to develop] a unified surface process science

83   that would integrate insight from all of the above fields to provide a comprehensive and predictive

84   understanding of the dynamics of our planet's surface" (p.1). Whilst this viewpoint is grand,

85   integrative, and inspirational, it finds a counterpoint in the notion that the *general* answers that

86   science can provide are inextricably linked to the *particular* questions that different human societies

87   and communities wish to pose (see Richards and Clifford, 2008, for a closer look at the problem

88   through this lens). The role of humans has always been central to Earth System Science: for

89   Bretherton (1988), the activities of humans were supposed to be incorporated into predictions using

90   "scenarios" based on plausible trajectories of social behaviour. A clear example of the use of

91   scenarios to represent possible human behaviour is in the set of CO_2 emission scenarios published

92   in the International Panel on Climate Change (IPCC) Special Report on Emissions Scenarios

93   (IPCC, 2001). Nevertheless, as Liverman and Roman-Cuesta (2008, p. 1458) explain: "for

94   interactions between the social and earth to succeed, a certain level of tolerance and mutual

95   understanding will be needed so that the social scientists understand the earth science aspiration for

96   quantitative socioeconomic scenarios and predictions, and earth scientists understand the variation

97   in how social scientists explain human behaviour and institutions and accept the clear limits to

98   predicting human activities and decisions".

99

100   The approach of the present review will be first to quantify the growth of Earth System Science as a

101   motivator of research grant funding and in publication trends. Second, I shall consider three sets of

102   key geomorphological studies, which contribute to the aims of Earth System Science, and which

103   themselves are informed by a deeper understanding of the importance of interactions in the Earth

104   System.

105

106   **3. Research trends**

107   Funding and publication trends can be assessed using publicly-available metrics, such as those

108   released by funding bodies and records of citations such as the Science Citation Index (SCI).

109   Clearly, these sources are not infallible: much good research is done outside the auspices of

110   mainstream funding; and the Science Citation Index captures work published in a finite range of

111   journals, potentially missing many pieces of work published in other forms such as research reports

112   and books. Nevertheless, these sources of information provide a suitable indicator of research

113   trends. For example, over the past eight years, funding from the UK Natural Environment Research

114   Council (NERC) for Earth System Science has increased from under £1m to over £6m (Figure 1).

115   Indeed, Earth System Science now features as a distinct 'theme' within NERC's funding strategy.

116   This funding has been directed to a number of high-profile collaborative and interdisciplinary

117   projects, including QUEST (Quantifying the Earth System), SOLAS (Surface Ocean Lower

118   Atmosphere Study), and IODP (Integrated Ocean Drilling Programme). Of course, it is possible that

119   increase results from a recognition by applicants that Earth System Science is a promising field of

120   enquiry rather than through an organic evolution of interest in the topic. As Figure 2 illustrates, over

121   half of the money allocated to Earth System Science was spent in Geography and Earth Science

122   departments. A 20 percent share of the overall spend occurred in departments where these two

123   disciplines had been amalgamated. A further 26 percent of the total was spent in 'traditional'

124   science departments (physics and maths, chemistry, biology), and the balance of 18 percent was

125   allocated to directly-funded Research Council facilities such as the British Antarctic Survey, British

126   Geological Survey, National Oceanography Centre, and Centre for Ecology and Hydrology.

127

128 The number of publications containing the term "Earth System Science" in the topic field has

129 increased from under 50 in 1988 to over 400 in 2004 (Figure 3), although there is considerable

130 inter-annual variability (and a problematic hiatus in 2002–3). The top five disciplines contributing

131 to the growth in popularity of the term "Earth System Science" in the literature are: engineering,

132 geology, physics, environmental sciences and ecology, and geochemistry and geophysics.

133 Geography (as a search term) ranks 21st in the list of Earth System Science disciplines, producing

134 less than two percent of the total publication output. Given the strong emphasis placed by

135 geographers on interactions between human and physical components of the Earth System, there is

136 a clear opportunity here. Of course, there is no separate record of publications from *physical*

137 geography and much of the work produced by the latter sub-discipline will undoubtedly have been

138 recorded in one of the other five preceding categories.

139

140 **4. Geomorphology in the Earth System**

141 The increase in research funding and publications relating to Earth System Science has led to a

142 partial re-orientation of research questions. Instead of pursuing finer and finer detail in simulations

143 of environmental systems, there is a recognition that coarser-scale models with reduced complexity

144 can contribute to collective understanding of interactions between components of environmental

145 systems. Richards and Clifford (2008) provide a stimulating philosophical and sociological

146 discussion of this trend; my aim here is to pick out several key strands of the debate using three

147 examples of environmental systems in which geomorphology plays a key role: (i) the links between

148 topography, global tectonics and atmospheric circulation; (ii) the link between geomorphic

149 processes and biogeochemical cycles; and (iii) links between biological processes and the earth's

150 surface.

151

152 *4.1 Tectonic uplift and Cenozoic climate change*

6

153　The role of earth-surface processes in interactions between the lithosphere, atmosphere and

154　hydrosphere has received renewed interest on a global scale over the past twenty years. Erosion

155　controls the topographic evolution of active mountain belts (Koons, 1989; Beaumont *et al.*, 1992;

156　Willett, 1999) and is the main source of sediment delivered to the sea (Milliman and Syvitski,

157　1992). Climate-driven erosion removes surface material, which modifies the topographic expression

158　of tectonic processes and alters the state of stress in the lithosphere (Molnar and England, 1990;

159　Willett, 1999). In turn, construction of mountain belts modifies global and regional atmospheric

160　circulation patterns and composition (Kutzbach *et al.*, 1989) because atmospheric carbon dioxide is

161　consumed by rapid weathering of fresh silicate crust exposed in active orogens (Raymo *et al.*,

162　1992), and particulate organic carbon is buried in nearby sedimentary basins (Lyons *et al.*, 2002;

163　Hilton *et al.*, 2008).

164

165　In the context of Earth System Science, which is concerned with interactions between processes

166　across different time- and space-scales, erosion provides a two-way link between tectonics and

167　climate. This link is especially effective in active, compressional orogens which deliver most clastic

168　sediment and a significant component of the chemical and organic discharges to the ocean, and it is

169　to these settings that much attention has been directed (Milliman and Syvitski, 1992; Gaillardet *et*

170　*al*., 1999). The links between erosion, climate, and tectonics vary across time-scales, from enhanced

171　erosion associated with individual earthquakes, to feedbacks between orographic precipitation and

172　the growth of mountain topography. Thus observations of erosion rates across multiple time-scales

173　provide essential information on the links between climate, tectonics, and topography. Mountain

174　erosion rates have been successfully quantified in localized areas (e.g., Burbank *et al.*, 1996;

175　Burbank *et al.*, 2003; Dadson *et al.*, 2003; Reiners *et al.*, 2003; Wobus et al., 2003), and attempts

176　have been made to predict long-term erosion rates from present-day relief and precipitation (e.g.,

177　Finlayson *et al*., 2002).

178

179   The feedbacks between focused climate-driven erosion and the tectonic evolution of entire

180   mountain belts are most clearly shown in geodynamic models of orogenic evolution. These models

181   range in complexity from simple analytical models of critical wedge topography (Davis *et al*., 1983)

182   to more complicated numerical simulations of the links between tectonic and erosional processes

183   (Willett, 1999). Critical wedge models treat the crust as a plastic frictional material in front of a

184   moving backstop. The material deforms so that it attains the minimum taper angle at which it can

185   slide on its base. The slope of the wedge reflects a balance between gravitational stresses arising

186   from the surface topography and basal shear stresses resulting from stronger material underthrust

187   beneath. The wedge grows by continued accretion, whilst its shape remains the same. The balance

188   between the tectonic mass flux and erosional mass flux determines the rate of orogen growth. If

189   tectonic input and erosional output are equal, the orogen is in a flux steady state and its size and

190   deformation fronts will not change (Willett and Brandon, 2002). If the tectonic input exceeds

191   erosional output, the orogen will grow through outward propagation of its deformation fronts. If the

192   erosional output exceeds the tectonic input, the zone of active deformation will reduce in size, and

193   previous deformation fronts will become inactive. It is important to note that spatial variations in

194   erosion rate will lead to locally varying deformation and rock uplift. If erosion is focused in areas of

195   high precipitation, the crustal deformation field will adjust to maintain the critical taper. This

196   mechanism can produce local zones in mountain belts through which rock mass is advected and

197   eroded (Willett, 1999; Beaumont *et al*., 2001).

198

199   Willett (1999) investigated the coupled system of uplift and erosion using a finite element, plane

200   strain model of deformation with a stream power erosion model of bedrock incision. The numerical

201   model showed that if erosion rates are low, crustal thickening continues until the lower crust is

202   sufficiently warm that it flows laterally. This flow prevents further thickening, promotes outward

203   propagation of the deformation fronts, and leads to the formation of a high elevation plateau. An

204   example of such a plateau is the Altiplano in the central Andes, the location of which coincides with

205   low precipitation rates (and therefore presumably low erosion rates; Willett, 1999; Montgomery *et*

206   *al*., 2001). Willett (1999) showed that adding erosion to his model led the topography to attain a

207   steady-state in which elevation was constant over time. Fundamental results of this model included

208   asymmetric topography with shallower slopes facing the subducting plate, and an asymmetric

209   pattern of exhumation with the deepest levels opposite to subduction (Figure 5). In subsequent

210   numerical simulations, Willett (1999) added asymmetrically-varying precipitation across the

211   mountain belt, to represent orographically-enhanced precipitation in response to a dominant

212   regional wind direction. This addition modified the first-order orogenic features. With the dominant

213   wind and moisture flux in the direction of subduction, a broad zone of exhumation was predicted,

214   with maximum exhumation in the orogen interior. This case is similar to the situation in the

215   Olympic Mountains of Washington State, USA, where metamorphic index minerals and fission-

216   track thermochronometry have shown a broad, bull's-eye pattern of exhumation, which is deepest in

217   the area well behind the leading edge. In the contrasting case, with a dominant wind in the opposite

218   direction to subduction, the model predicted a focused zone of exhumation at the margin of the

219   orogen.

220

221   The results from coupled geomorphic and geodynamic models suggest that climate-driven erosion

222   is of first-order geophysical significance in the evolution of mountain belts across a range of time-

223   scales. However, the recent advances in modelling have outpaced the analysis of relevant field

224   observations, with the result that most models are underconstrained. The links between erosion,

225   tectonics, and climate are complex and understanding them requires detailed quantitative

226   observations of erosion, and better constraints on the rates of climatic and tectonic process that

227   drive erosion across a range of time-scales. Important questions that must be addressed are: what

228   processes drive, and limit, the rate at which crustal material is removed from mountain belts? Do

229   erosion rates inferred from topography match measured erosion rates? Are the dominant processes

230   that drive erosion consistent across time-scales ranging from decades to millions of years? How do

231   climate-driven erosional and tectonic processes interact to create topography on the scales of

232   individual faults and entire landscapes? Many of these questions have been investigated using

233   surface process models, but real world patterns are not well known and further progress requires

234   quantitative observations of mountain erosion across a range of time-scales.

235

236   A controversial feedback was proposed by Molnar and England (1990), who claimed that in the late

237   Tertiary and Quaternary the global shift to a cooler and more erosive climate has enhanced

238   topographic relief in mountain ranges. They argued that the isostatic response to increased erosion

239   of valley floors would raise mountain peaks higher. Moreover, higher peaks would accumulate

240   more snow, which would promote rapid glacial weathering and erosion. In turn, rapid silicate

241   weathering and erosion would withdraw atmospheric carbon dioxide and lead to further reductions

242   in global temperature.

243

244   The feedback proposed by Molnar and England (1990) has provoked much debate; it rests on the

245   assumption that the transition to a more erosive climate enhances mountain relief (Small, 1999;

246   Whipple *et al.*, 1999). In fact the opposite may be true, although in 1990 when Molnar and England

247   were writing only statistical studies had demonstrated that higher erosion rates were correlated with

248   reduced relief (Melton, 1957). Topographic relief at the scale of a mountain range consists of

249   hillslope and fluvial components. River incision can increase relief only if hillslopes can

250   simultaneously become steeper. This is possible only if hillslopes are shallower than their angle of

251   repose (van Burkelow, 1945). To investigate typical hillslope angles in rapidly-uplifting mountain

252   belts, Schmidt and Montgomery (1995) analysed slope profiles in the Washington Cascade Range,

253   and the Santa Cruz Mountains of central California, USA. These areas have both exhibited

254   widespread bedrock landsliding. Schmidt and Montgomery (1995) compared observed slope angles

255   with predictions from a model of hillslope stability based on a Coulomb-type failure criterion and

256   concluded that natural slopes do not become steeper than the angle of internal friction of the

257   material from which they are made. Accordingly, they proposed that mountain-scale material

258   strength places a limit on the topographic relief that can develop as a result of river incision.

259

260   Burbank *et al*. (1996) observed a similar situation to Schmidt and Montgomery (1995) in the north-

261   western Himalayas, near Nanga Parbat. Burbank *et al*. (1996) showed that, despite very rapid

262   erosion (2–12 mm yr^{-1}), average and modal hillslope angles are independent of erosion rate. They

263   suggested that slope angles are controlled by a common threshold process, which is dictated by the

264   material properties. Mean relief is set not by erosion rate but by the spacing of large rivers. Burbank

265   *et al*. (1996) proposed that a balance is maintained between bedrock uplift and river incision:

266   landslides allow hillslopes to adjust efficiently to rapid river downcutting. Moreover, the findings of

267   Burbank and coworkers (1996) imply that the greatest relief develops either where rocks are less

268   fractured (Schmidt and Montgomery, 1995), or where drainage density is lowest (Melton, 1957).

269

270   The studies by Schmidt and Montgomery (1995) and Burbank *et al*. (1996) demonstrate that in

271   many tectonically active mountain ranges, hillslopes fail by bedrock landsliding to keep pace with

272   bedrock river incision. This finding is important in understanding the relation between climate,

273   valley incision and the uplift of mountain peaks, because it challenges the assumption of Molnar

274   and England (1990) that relief can be increased by the incision of deep valleys. If hillslopes are

275   typically at their angle of repose, then changes in mountain relief can occur only through incision of

276   mountain rivers into bedrock, and rates of river profile evolution will dictate the link between

277   erosion and mountain scale relief.

278

279   Taken together, results from geomorphological modelling studies show that the links between

280   erosion, tectonics, and climate are complex. Much of the argument has been driven by modelling,

281   yet models are heavily parametrized and poorly constrained. Understanding natural patterns of

282   erosion requires more detailed, quantitative observations of erosion. Important questions that must

11

283 be addressed are: what are the relative roles of extreme and moderate floods in driving erosion rates

284 in tectonically active landscapes? Over what time-scales does climatic variability matter? Can

285 erosion rates be inferred from topography, and what is the role of substrate strength in determining

286 the expression of climatic and tectonic processes in topography? To answer these questions requires

287 observations of average erosion rates and their variability over a range of time-scales.

288

289 The work described so far clearly shows the importance of interactions in the Earth System. Recent

290 advances in our collective understanding of these interactions have involved simplifications of

291 several sets of dynamical processes that would be treated in a very different ways if they were the

292 sole focus of study (e.g., processes in fluvial geomorphology are increasingly treated using

293 approaches based on computational fluid dynamics (see Bates *et al.*, 2005, for some examples);

294 detailed modelling of strain rates in the continental lithosphere would adopt a similarly involved

295 procedure (see Jackson and McKenzie, 1988; Hu *et al.*, 2001 for two contrasting approaches). The

296 challenge presented by the papers described above (e.g., Willett, 1999) is to integrate these

297 processes at the appropriate time and space scales, with appropriate levels of conceptual

298 simplification. This is the central goal of Earth System Science. It is, of course, a goal familiar to

299 physical geographers, and this aim will no doubt strike a resonant note among geomorphologists

300 familiar with the analysis of Schumm and Lichty (1965), which demonstrates how processes can be

301 conceptualised at different scales.

302

303 *4.2 Geomorphology and biogeochemical cycles*

304 Rapid changes over the past decade have seen the role of earth-surface processes as drivers of

305 changes to biogeochemical cycles such as the carbon cycle. For example, rates of soil erosion are

306 sensitive to changes in surface runoff. Soils store a significant amount of carbon: globally, the

307 equivalent of approximately 200–300 times the amount of carbon released annually through the

308 burning of fossil fuels (Cox *et al.*, 2000). Any enhancement of soil erosion caused by changing

309 runoff can be expected to make a major contribution to carbon cycle feedbacks in a changing

310 climate. Indeed, preliminary estimates of large-scale soil carbon fluxes suggest that an important

311 component of this feedback may be attributable to the effects of soil movement by geomorphic

312 processes (Stallard, 1998). Nevertheless, the role of soil erosion and redistribution in the carbon

313 cycle remains an area of some controversy with estimates of the global carbon flux associated with

314 erosion ranging from a 1 Gt year^{-1} source to a 1 Gt year^{-1} sink (Stallard, 1998; Lal, 2003). The

315 magnitude of carbon redistribution by sediment erosion and deposition demonstrates the potential

316 for geomorphic processes to make a major contribution to the global carbon budget. For example,

317 Jacinthe and Lal (2001) estimate that 5.7 Pg C yr^{-1} are mobilised by water erosion. Soil erosion

318 exposes fresh material at the surface which results in a disequilibrium between soil carbon content

319 and crop carbon input that maintains a continuous supply of carbon for transfer to sedimentary

320 environments. Stallard (1998) has hypothesized that this conveyor of sediment-associated carbon

321 from hillslope to sedimentary environments has the potential to sequester atmospheric CO2 at the

322 rate of 1–2 Gt C yr^{-1} globally.

323

324 There is a clear research need to quantify the effects on the carbon cycle of soil erosion and

325 deposition, however, approaches capable of doing this at appropriate scales have yet to be

326 developed. A number of recent quantitative studies stand out in this respect. Lyons *et al.* (2002)

327 showed that over one third of the total particulate organic carbon flux from the land surface to the

328 ocean derived from sediment-laden rivers draining the mountainous western Pacific region.

329 Moreover, in a detailed study of the role of storm flows in triggering carbon delivery, Hilton *et al.*

330 (2008) have shown that, in the mountainous Li Wu River in Taiwan, between 77 and 92 percent of

331 modern particulate organic flux was transported during large, cyclone-induced floods. The impact

332 of land-management practices is also of potential importance. Indeed, recent hillslope-scale

333 modelling has shown that within-field soil redistribution, principally driven by tillage, has been

334 responsible for a net sink in the order of 5–10 g C m^{-2} year^{-1} over the last half century at two sites in

335   NW Europe (Van Oost *et al*., 2005). Quantification of feedbacks between the geomorphic system

336   and the carbon cycle offer a clear example of a critically-important scientific activity that is likely to

337   benefit from a funding framework influenced by Earth System Science

338

339   Another biogeochemically-active constituent of the geomorphic system is found in mineral dust

340   aerosols. As one of the most abundant atmospheric aerosols, mineral dust plays a key role in

341   determining the planetary radiation budget. Whilst this effect may be to increase the amount of

342   short-wave radiation reflected back into space (leading to a cooling effect), the presence of mineral

343   aerosols may also lead to increased absorption of outgoing long-wave radiation (having a warming

344   effect similar to that of greenhouse gases). The balance between the two is governed by the vertical

345   profile of dust concentration (Washington *et al*., 2008).

346

347   Dust aerosols also provide iron and other nutrients to marine phytoplankton populations and

348   terrestrial vegetation during deposition. Dust emissions occur in response to aeolian deflation, and

349   are controlled mainly by variability in vegetation, soil moisture, and surface erodibility. Dry low-

350   lying regions such as dry lake beds are the main source of African dust events (Ginoux *et al*, 2001;

351   Prospero *et al*, 2002; Washington *et al*., 2009). Consequently there are clearly potential feedbacks

352   involving dust associated with a changing climate. It is hypothesised that during glacial-interglacial

353   cycles, increases in the dust supply of iron to the ocean resulted in a significant Earth system

354   feedback, driving about one third of the observed glacial-interglacial variations in atmospheric CO_2

355   (Kohfeld *et al*., 2005). Some early studies (e.g., Tegen & Fung, 1995) have found that, in the

356   modern setting, human influences have increased dust emissions directly via changes in land use by

357   as much as 20–50 percent (Tegen *et al*, 1996; Sokolik & Toon, 1996). However, more recent

358   estimates have revised the anthropogenic increase to be less than 10 percent (e.g., Tegen *et al*.,

359   2004; Prospero *et al.*, 2002). Further work is clearly required to quantify the potential effect of a

360 future climate change scenario on dust emission, transport, and deposition, through to their effect on

361 the ocean carbon cycle.

362

363 *Geomorphology and the biosphere*

364 The role of vegetation in geomorphic processes has been the subject of research ever since

365 Darwin's study of the effect of earthworms on reworking of soil organic matter (see Kennedy,

366 2006, for a review). Nevertheless, one of the stated aims of Earth System Science is to examine

367 linkages between the lithosphere, hydrosphere, atmosphere *and* biosphere. Before the explicit

368 emergence of the Earth System Science paradigm, the work of Langbein and Schumm (1958) was

369 influential in demonstrating the links between climate, vegetation, and erosion. These authors

370 showed that rather than scaling simply with precipitation rate, erosion rates were highest in semi-

371 arid climates (rather than arid or humid climates), because in these regions, there was sufficient

372 precipitation for erosion to occur, but insufficient to ensure perennial vegetation cover. More recent

373 reviews by Viles (1988), Naylor *et al*. (2002) and Stallins *et al*. (2006) have summarised the many

374 developments in the field of biogeomorphology to date.

375

376 Whilst the role of biota in governing geomorphic process rates has been recognized, Dietrich and

377 Perron (2006), recently turned the question around, asking: "is there a topographic signature of

378 life?" That is, would a unique set of topographic properties be evident in a map from which all

379 vegetation and artefacts of human activity had been removed. The motivation for this question

380 illustrates the role that Earth System Science can play in setting the range of appropriate questions.

381 Although not stated explicitly, Dietrich and Perron's (2006) paper clearly addresses a key aim of

382 Earth System Science. The basis of Bretherton's original manifesto was that NASA should embark

383 on a mission to Planet Earth. Clearly, if it is possible to detect life topographically (i.e., by

384 measuring nothing more than the elevations of points on a planet), then exploration for extra-

385 terrestrial life is immediately made much easier.

386

387   Dietrich and Perron (2006) structure their analysis to consider three distinct, but connected,

388   questions: (i) what is the influence of biotic processes on weathering, erosion, and sediment

389   transport mechanisms; (ii) how do biotic processes affect climatic and tectonic processes globally;

390   and (iii) what are the implications of biogeomorphic processes for the development of topography

391   in abiotic environments. In addressing the first question, it is clear that biological processes can

392   exert a strong control on the rates and styles of geomorphic processes such as soil production and

393   creep (through animal burrowing, tree throw and root growth), landsliding (through enhanced root

394   cohesion and provision of surface cover), debris flows and river incision (via presence of large

395   woody debris in channels). As Dietrich and Perron (2006) note, a key challenge is to develop

396   geomorphic transport laws which represent these processes in ways that can be justified with

397   reference to high-quality field data. Nevertheless, even with a preliminary understanding of such

398   processes, model experiments are already providing qualitative explorations of the effects of biotic

399   processes on landforms (see Kirkby, 1995 and Collins *et al.*, 2004). Indeed, Istanbulluoglu and Bras

400   (2005) have demonstrated numerically that changes in vegetation cover can lead to a transition from

401   runoff-dominated erosion to landslide-dominated erosion (Figure 6)

402

403   In a thought experiment, Dietrich and Perron (2006) also consider what climate and tectonics would

404   look like without the presence of life. They note that an obvious consequence of the removal of

405   biotic influence would be a "rapid erosion of the soil mantle that covers semi-arid to wet

406   landscapes" (p. 413), but they go further to state that it is not correct to suppose that the presence of

407   "smooth, rounded, soil-mantled hillslopes are a topographic signature of a biotic world" (p.413).

408   They key point here is that whilst biotic processes interact strongly with the lithosphere through

409   geomorphic processes, the link does not result in a unique topographic form. There is an element of

410   equifinality in the system under study, in the sense that the same set of physical features can be

411   created by a range of different processes and that it is not possible to attribute a particular cause to

412   their creation (see Schumm, 1991 for further discussion). The answer that Dietrich and Perron

413   arrive at is illuminating, not only because it reveals how the earth's surface is a critical site for

414   interactions in the earth system, but also because their analysis demonstrates how Earth System

415   Science can itself benefit from an understanding of some of the older concepts that have emerged in

416   earlier studies of complex systems in physical geography (such as equifinality, emergence,

417   interactions of processes across a range of time- and space-scales; see Schumm, 1991, for a detailed

418   review).

419

420   **6. Geomorphology in ESS: revolution, evolution or recapitulation**

421   The conclusions to the previous section raise several key questions for the future of geomorphology

422   in Earth System Science. According to Paola et al.'s (2006) analysis, the greatest need is for better

423   collaboration between the many disciplines that pertain to geomorphology. This integration can

424   happen only when opportunities are sought for geoscientists to exchange ideas with colleagues from

425   other disciplines. In practice, this can actually be quite challenging: one is forced out of one's

426   comfort zone. Yet numerous biographical accounts of major interdisciplinary scientific

427   achievements reveal the range of strategies that may be employed (see, for example, the accounts

428   by Peter Molnar and Dan McKenzie, in Oreskes, 2003). There may well be some technical

429   solutions: better training in advanced mathematics is an obvious way to equip geoscientists with a

430   *lingua franca* with which to communicate with a wider range of other scientists. Better mathematics

431   should also mean smarter mathematics: not just fiddling about with a complicated computer

432   simulation until it produces results that look a bit like the real world (see Molnar, in Oreskes, 2003,

433   for a more florid description of the drawbacks of such an approach), but understanding how to make

434   appropriate simplifications to a model of, say, river channel dynamics so that it may communicate

435   with a model of, say, ecological succession or climate change. Beyond the technical challenge of

436   enabling communication between geoscientists of different backgrounds is the need to include

437   social science in Earth System Science. Here, Liverman and Roman-Cuesta (2008, p.1459) note the

438   considerable barriers: "At worse, earth scientists sometimes assume that the role of the social

439   sciences is little more than that of a public relations effort to translate science to stakeholders. In

440   other cases earth scientists believe that the qualitative nature of some social science research sets

441   insurmountable barriers to integrated analysis or modelling". Insofar as geographers possess skills

442   and interests that can bridge the potential barriers between natural and social science, they are well

443   placed to advance the debate. The challenge in the coming years will be for University departments,

444   research institutes, funding bodies, and learned societies to provide suitable training and research,

445   funding, and networking opportunities in order for this potential to be realised.

446

447   Aside from these practical needs, some more conceptual issues are raised by the rise of Earth

448   System Science. Whilst it should of course be clear that it is possible to pursue rigorous and

449   meaningful research in geomorphology without involving or appealing to the imperatives of Earth

450   System Science; and, conversely, it is possible to understand major parts of the Earth System

451   without developing anything more than a cursory concept of geomorphology. However, where there

452   *is* a meaningful interface between geomorphology and other components of the Earth System (and I

453   hope to have introduced a wide-ranging set of examples of such circumstances), three key questions

454   arise: (i) explanation and scientific method for earth systems science; (ii) questions of time and

455   space scales and links between process operating at different scales; and (iii) the status of humans as

456   actors/agents in a framework defined by Earth Systems Science. These are not trivial questions, and

457   they cannot be approached as afterthoughts. They will require changes to the curriculum; they will

458   require changes to funding frameworks. But the rewards that come with an integrated understanding

459   of the earth system can be great: from more robust models of the effects of climate and land-use

460   change on geomorphic processes, to a greater understanding of interactions of physics, chemistry

461   and biology. Physical geographers have a significant contribution to make, not just to the

462   integration of knowledge of the biosphere, lithosphere, hydrosphere and atmosphere; but to the

463 detailed and nuanced ways in which the actions of and impacts upon human societies can be

464 enumerated, quantified, and communicated.

465

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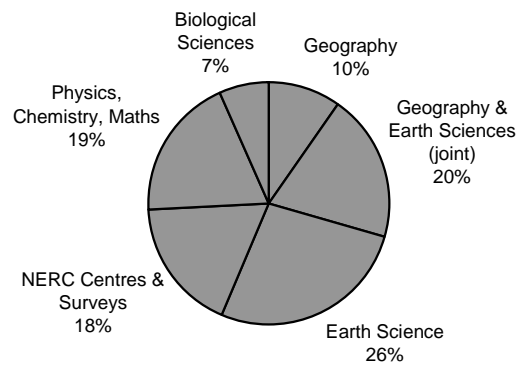
604 **FIGURES**

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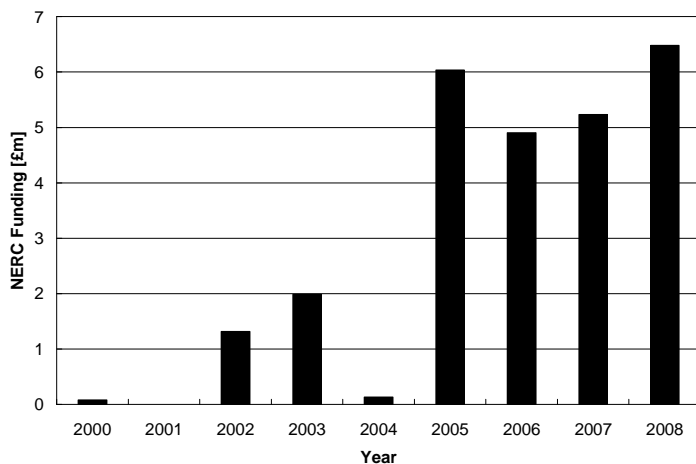
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607

608 Figure 1: Funding by year from the UK Natural Environment Research Council for grant,

609 fellowship and training awards containing the phrase "Earth System" in the title or abstract.

610 Publicly-accessible data source http://gotw.nerc.ac.uk/, accessed 14th June 2009.

Figure 2: Breakdown of NERC research funding by discipline. from the UK Natural Environment Research Council for grant, fellowship and training awards containing the phrase "earth system" in the title or abstract. Publicly-accessible data source http://gotw.nerc.ac.uk/, accessed 14th June 2009.
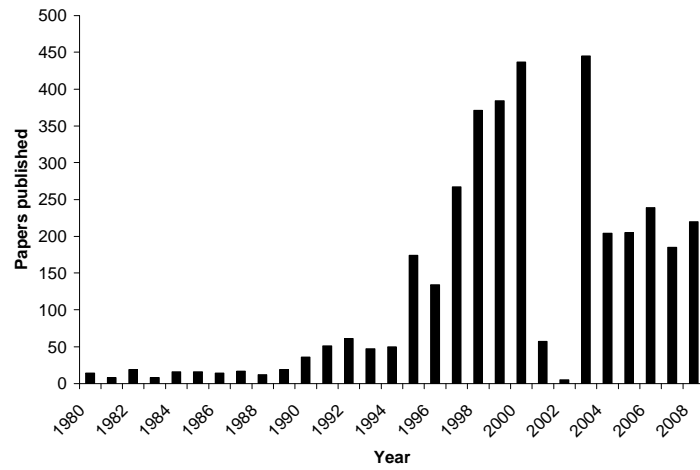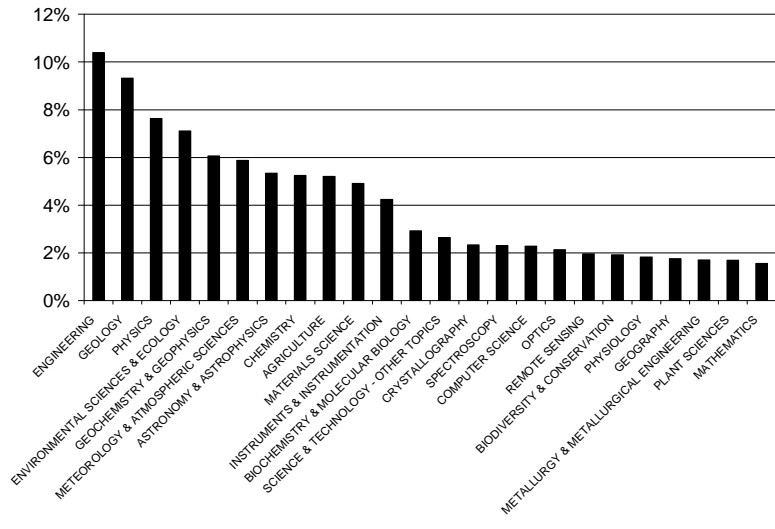
617

618 Figure 3: Annual number of publications in the ISI Web of Science database where the topic field

619 contains the phrase "Earth System Science". (Source: http://wos.mimas.ac.uk/, accessed 14th June
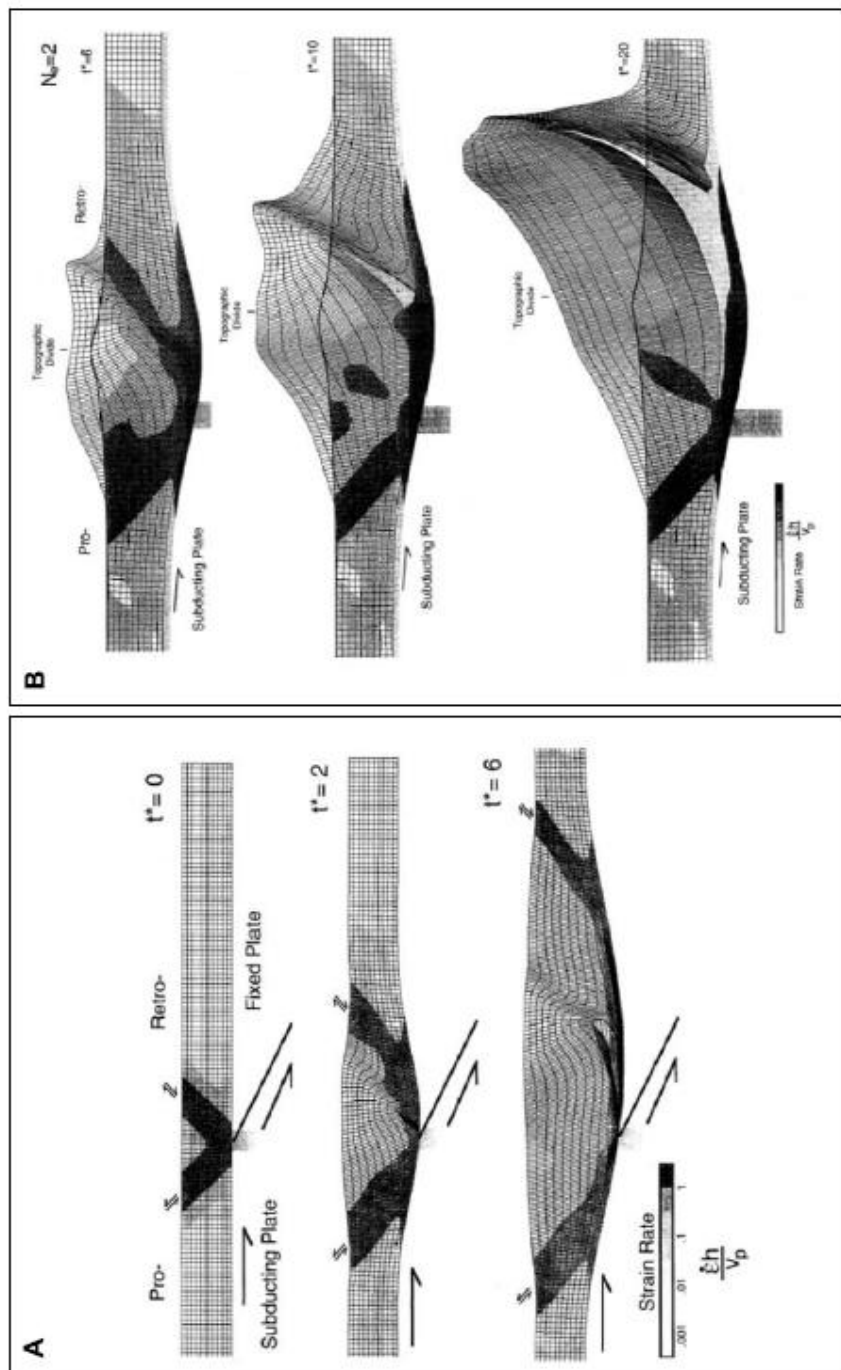
620 2009).

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624 Figure 4: Publications in the ISI Web of Science database, broken down by discipline, where the

625 topic field contains the phrase Earth System Science. (Source: http://wos.mimas.ac.uk/, accessed

626 14th June 2009).

627

Figure 5: Finite element model for viscous-plastic deformation during convergence (Willett, 1999).

Subduction is to the right, with a constant velocity applied at the base of the crustal layer. The

applied velocity is zero to the right of the grey block. Coulomb friction angle is 15 degrees. Below

the Coulomb yield stress, crust deforms according to a temperature-dependent viscous constitutive

relation. Time is nondimensionalized by (subduction velocity / crustal thickness) to give t^*. The

Argand number is initially 0.5 at the base of the crustal layer. Shading indicates the instantaneous

634   nondimensional strain rate. The pro-wedge moves in the direction of subduction, against the retro-

635   wedge. The mesh follows particle motion and indicates total deformation. In cases with erosion the

636   topographic surface is shown in bold. A, no erosion; B, uniform erosion with $N_e = 2$. The erosion

637   number characterizes the erosion rate relative to the rate of rock uplift.
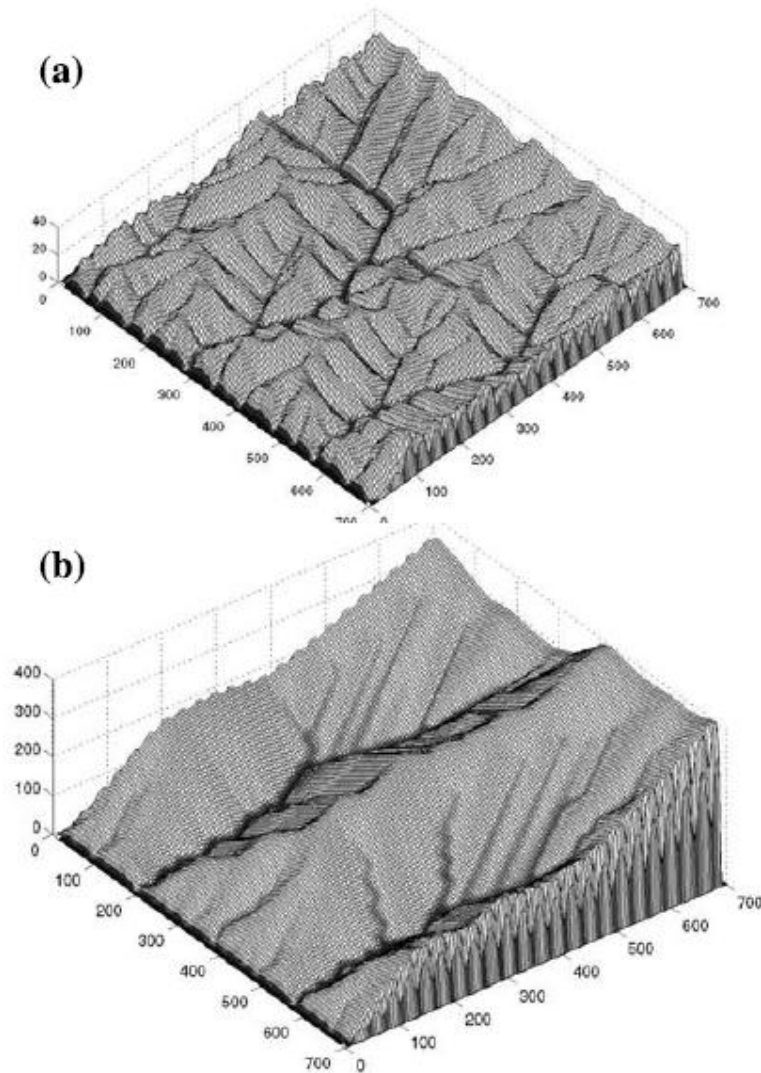
638

639   Figure 6. Results of numerical simulations showing the difference between landscapes simulated

640   with (a) no vegetation cover and (b) static vegetation cover. Both landscapes are in topographic

641   steady-state, where there is no trend in mean elevation over time (although inevitable fluctuations

642   about a long term mean occur due to stochastic climate forcing and static erosion thresholds). From

643   Istanbulluoglu and Bras (2005).