Spatial Modelling of the Terrestrial Environment

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For Hannah, Oscar, Rita and Geoff

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Preface

This book contributes to the diverse and dynamic research theme of advances in remote sensing and GIS analysis. Continuing the tradition of other edited volumes, it is the product of a stimulating meeting organized jointly by members of the U.K. Remote Sensing Society's (now Photogrammetry and Remote Sensing Society) Modelling and Advanced Techniques (MAT) and Geographical Information Systems (GIS) Special Interest Groups (SIG). These two SIGs hold regular meetings and are an invaluable forum for vibrant discussions between undergraduates, graduates, professional academics and practitioners of GIS and environmental modelling. This particular meeting was held at Birkbeck College, University of London on 17 November, 2000 and attracted about 100 delegates.

The plan to organize a one-day meeting was originally hatched (perhaps during a reckless moment of bravado) at the 1999 annual conference of the Remote Sensing Society in Cardiff. Convened by Nick Drake, Stuart Barr and Richard Kelly, the one-day symposium was slightly different to previous meetings in that the theme was more narrowly focussed than before. Speakers were asked to present aspects of their research and how it relates to spatial modelling of terrestrial environments, one of the themes running through both MAT and GIS SIGs. Ten speakers presented their up-to-date research and there was plenty of scope for some vibrant discussion and exchange of ideas. From the ten presentations, six are included as chapters in this book and five new contributors were sought to enhance the existing contributions, and also add an international dimension to the volume. To provide some context for the different contributions, we have also included our own personal views about the three broad areas of applications and how spatial modelling is an important strand running through each application. These are personal views that offer our own interpretation on some very rapidly advancing GIS and modelling fields.

We hope that the book will be useful for students and researchers alike. Inevitably, there are omissions in the topics covered and responsibility for any omissions lies squarely with the editors. Furthermore, most of the topics covered in this volume are rapidly evolving in theory and application and many new research themes have recently appeared and are pushing forward rapidly at both the national and international research levels. Ultimately, while we do not claim to cater to all needs and interests, we feel that there are some important issues raised in the book that apply to the integration of remote sensing data with spatial models and trust that there are some ‘nuggets’ for interested academicians and practitioners in this dynamic field.

A book such as this cannot come into existence without the assistance of many people involved both with the organization of the symposium and the production of the book. For sponsoring the original meeting we are very grateful to the Photogrammetry and Remote Sensing Society, Birkbeck College, University of London, Kings College London and Leeds University. We would also like to thank the local organizing committee, especially Tessa Hilder, Chloe Hood and Matt Disney. In connection with getting the book to print and for their invaluable guidance and help in steering the editors through the publishing maze, we would like to sincerely thank John Wiley & Sons, particularly Lyn Roberts and Keily Larkins.

Richard Kelly, Nick Drake and Stuart Barr

1

Spatial Modelling of the Terrestrial Environment: The Coupling of Remote Sensing with Spatial Models

Richard E.J. Kelly, Nicholas A. Drake and Stuart L. Barr

'The creation of silicon surrogates of real-world complex systems allows us to perform controlled, repeatable experiments on the real McCoy. So, in this sense complex system theorists are much in the same position that physicists were in the time of Galileo, who was responsible for ushering in the idea of such experimentation on simple systems. It was Galileo's efforts that paved the way for Newton's development of a theory of such processes. Unfortunately, complex systems are still awaiting their Newton. But with our new found ability to create worlds for all occasions inside the computer, we can play myriad sorts of what-if games with genuine complex systems' (Casti, 1997).

1.1 Introduction

The objective of this book is to present snapshots of research that are focused on spatial modelling approaches to terrestrial environmental problems. With thirteen chapters covering three broad environmental areas, the contributions concentrate on examples of how models, particularly numerical models, can be used spatially to address a variety of practical issues. This objective seems fairly straightforward except that when we consider precise definitions, things start to get a little 'fuzzy'. For example, at first glance the *terrestrial environment* is simple enough to define since it relates to conditions, processes or events that occur on the land portion of the Earth surface. However, when we connect it to *spatial modelling*, we might need to consider land–atmosphere–ocean interactions that help to condition the purely terrestrial environment. Therefore, how should these distinctly non-terrestrial

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components be represented? Many Earth system scientists adopt a wider and more holistic approach to spatial modelling and, with powerful computational assistance, have been able to satisfy large-scale modelling demands. Spatial models can range from simple point process models that are spatially distributed to complex spatially referenced mathematical operations performed within the context of geographical information science (GISc). And what about the data that we use to input to our spatial model? Perhaps remote sensing data are among the most obvious data types that could be harnessed for spatial modelling. In fact, if we reduce remote sensing products to their bare bones, they are probably one of the simplest forms of spatial models or spatial representation of the terrestrial (or perhaps planetary) environment. Physical remote observations from spatially discrete and often separate locations on the earth are converted to information via some algorithm or model. The derived information actually represents a spatial variable or geophysical parameter making the data implicitly spatial as an input to an environmental model. Therefore, the nature of spatial modelling of the terrestrial environment seems to have a fairly broad scope and could include many diverse scientific activities. Consequently, the objective of this book is to present a range of spatial modelling examples and to demonstrate how they can be used to inform and enhance our understanding of the terrestrial environment and ultimately pave the way to an increased accuracy of model predictions.

We have chosen to focus on the terrestrial environment primarily for reasons of self-interest. For readers seeking a more general collection, there have been several excellent recent volumes that have documented the general theme of advances in geographical information systems (GIS) and remote sensing (e.g. Foody and Curran (1994), Danson and Plummer (1998), Atkinson and Tate (1999), Tate and Atkinson (2001) and Foody and Atkinson (2002)). The fact that these volumes are highly successful is due to the high quality of the contributions, and because the editors have expertly assembled some key applications in GIS and remote sensing, both of which are dynamically interlinked and rapidly evolving sub-disciplines within geography, Earth and environmental science. For a flavour of the activity in GIS alone, the reader is directed to the comprehensive 'Big Book of GIS', now in its second edition (Longley *et al.*, 1999). We have taken a slightly different tack to these previous volumes in that we have attempted to couple the advances in remote sensing, GIS and modelling to a particular application theme, namely the terrestrial environment. In doing so, there is much that we have not covered with respect to both the terrestrial environment and the more theoretical aspects of spatial modelling. However, in understanding and perhaps predicting the terrestrial environment, the scientist often is less concerned with sub-discipline specific categorizations and more concerned with bringing these strands together to help solve a problem. We feel that not only does this book serve this purpose but also illustrates the diversity of approaches that can be taken and shows the way the field is heading.

1.2 Spatial Modelling

While the literature on general model theory is vast, the general aims of modellers usually consist of improving our understanding of a phenomenon (process, condition, etc.), simulating its behaviour to within a prescribed level of accuracy and ultimately predicting future states of the phenomenon (Kirkby *et al.*, 1993). In general, these aims are linearly related; increased environmental understanding often leads to improved simulation capability which can, but not always, result in more accurate prediction. While not wishing to become immersed in the many different modelling critiques, there are a few key aspects that are instructive for the modeller. Casti (1997) proposed four fundamental characteristics that can provide insight into the utility of a model: simplicity, clarity, bias-free and tractability. These four qualities should be self-evident for modellers. Tractability is possibly the most important property for the overall design of modern computer modelling since it relates to the ability of a computer model to undertake the task efficiently and not at a disproportionate computational cost. With increasingly complex models becoming the norm, there is sometimes a sense that the model is 'too big' for the task and that disproportionately large amounts of computer 'brawn' are needed to solve a relatively trivial problem (akin to requiring a 'sledgehammer to crack open a nut'). This is especially important when we extend models to become spatial in implementation.

A key question that modellers often need to address, then, is 'how is spatiality woven into the application?' Spatial models in GIS have generally considered the concept of data model, particularly vector and raster model representations of data (Burrough and McDonnell, 1998). More recently, research has focused on approaches that define objects or fields in geographical data modelling and most recently, Cova and Goodchild (2002) have proposed a methodology to produce fields of spatial objects. Since remote sensing data are generally rasterized, many spatial models are configured with grid cells. While this is a convenient computational device, Cracknell (1998) notes that in fact, remote sensing information rarely represents regular square fields of view. Rather, instantaneous fields of view are usually elliptical in geometry, a function of the physics of many Earth observation instruments. Thus, remote sensing data tend to be distorted to fit the modelling spatial framework that is often based on a square cell arrangement. In discussing developments of environmental modelling and the need to 'future-proof' modelling frameworks Beven (2003) observes, 'it is often inappropriate to force an environmental problem into a raster straitjacket. Treating places as flexible objects might be one way around (this) future-proofing problem.' Spatial modelling of the terrestrial environment, therefore, needs to be sensitive to this issue but as yet, most modelling approaches remain fixed in the regular grid cell or raster mode of spatial representation.

A key theme that is associated with spatial modelling is scale which Goodchild (2001) terms the 'level of detail' in a given geographical representation of the Earth's surface. Scale affects directly all four of Casti's qualities in modelling (clarity, simplicity, bias and tractability). With increased computer power and increased spatial resolution, there is a tendency towards increased spatial variation, which may or may not be required. If we also consider the gradual technological improvement of remote sensing spatial resolving power, the level of detail at which scientists can model has increased over the years. However, modellers have to use their judgement with respect to the appropriate spatial scale that is, (a) possible, and (b) required. For example, to model soil moisture spatial variability, it probably does not make sense to compute estimates at a 10×10 m spatial resolution if the scientist is interested in regional drought conditions: 500×500 m might be sufficient. Moreover, the tractability of the model might be called into question when using such a fine spatial resolution. Understanding this spatial dependence of the property to be modelled is an important aspect of scale selection but one that is sometimes neglected. Ideally, spatial dependence should determine the spatial framework of the model from the outset.

Current spatial frameworks available to environmental modellers can cater for most scales of spatial variation at the local to regional scale. Models often can be constructed using desktop computer hardware either using standalone or clustered node architectures. However, at the other end of the extreme, the regional-to-global scale (such as coupled land–ocean–atmosphere models) is less well catered for or researchers need to have access to very expensive and powerful multi-parallel processing computers. Even then, there are computational limits to what models can achieve especially with the demand for increased model complexity. The limitations can be pushed back by a coordinated infrastructure approach at the international research community level (Dickinson *et al.*, 2002). Two approaches have led to the Program for Integrated Earth System Modelling (PRISM) in Europe and to the Earth System Modeling Framework (ESMF) in the USA (Ferraro *et al.*, 2003). The general goals of these initiatives are similar in scope since they both aim to increase model interoperability across the Earth system science research community. In doing so, scientists will be able to compare models within a standardized and scaleable modelling framework. The aims are to enable improved model simulation and potentially identify computational technology developments (both hardware and software) required to satisfy the need for increasingly complex models over broad space and time scales. If successful, these initiatives will pave the way for the next generation of Earth system science models.

1.3 Summary of the Book

The scope of spatial modelling of the terrestrial environment is broad in its application. This is reflected by the diversity of applications and examples that are included in this book. Running through all of the contributions are three common threads that make the title of this book appropriate. First, all chapters describe mathematical operations on spatially referenced data that are a representation of a terrestrial state variable, both natural environmental and human environmental. Second, most contributions describe applications that are reliant on the use of remote sensing data as input variables to a modelling environment. Those that do not, use spatially referenced information from other authorized sources. Third, many of the contributors use geographical information systems (GIS) technology (some more formally than others) to help perform modelling procedures.

The book is divided into four Parts, which reflect the contributors' interests: hydrological applications, terrestrial sediment and heat flux applications and urban system dynamics applications. The hydrological applications Part begins with a chapter by Jonathan Bamber who discusses and demonstrates the application of radar altimetry and synthetic aperture radar (SAR) interferometry data for the estimation of ice sheet topography. Ice sheet topography is critical for numerical models that predict ice sheet dynamics and, thus, provide a means of estimating an ice sheet's mass balance. In the next chapter Richard Kelly *et al.* investigate how numerical hydrological models and passive microwave remote sensing observations of snow mass can be used to retrieve global snow volume. In this example, models are used both in hydrological simulation and in the retrieval algorithms that recover snow parameters such as snow depth. They also investigate spatial dependence characteristics evident in ground measurements and remote sensing observations of snow depth. Eleanor Burke *et al.* in Chapter 4 then describe how land surface and microwave emission models can be coupled to increase the accuracy of estimates of soil moisture from ground-based and aircraft radiometer instruments. The rationale for this work is to pave the way for accurate soil moisture retrievals from planned satellite missions designed for global soil moisture monitoring. Finally, in the last chapter of this Part, Paul Bates *et al.* demonstrate how LiDAR and SAR data can be combined with the prediction of flood inundation through their coupling to a numerical flood model.

Part II illustrates how models and remote sensing are used in terrestrial sediment and heat flux modelling. The first chapter in this Part by Stuart Lane *et al.* examines how the knowledge of errors in the derivation of digital elevation models from remote sensing data is an important component of river channel research and must be effectively managed. Understanding, quantifying and ultimately reducing errors in models not only can reflect model confidence but it can also provide insight into how the model can be improved. In Chapter 7, Greg Okin and Dale Gillette show how ground-measured wind vectors can be used to model wind erosion and dust emission. The rationale for this chapter is to explore the relative contribution of natural and land use sources of dust emission to local or regional wind erosion patterns. By quantifying micro-scale to local-scale variations in emission and the controlling processes, coarser-scale models should benefit through increased accuracy. In Chapter 8 by Nick Drake *et al.*, remote sensing data are coupled to a regional-scale soil erosion model to examine biodiversity on Lake Tanganyika. While they discuss some of the shortcomings such as the errors associated with the remote sensing products used (e.g. the normalized difference vegetation index), they show that such an approach has great promise for biodiversity monitoring of remote locations. Chapter 9 by Martin Wooster *et al.* deals with the estimation of fire radiant energy from different satellite remote sensing instruments. This information is then coupled to a model to estimate vegetation combustion, a variable that is proportional to the rate of release of pollution species. Such an application is of great interest to many regions of the world where fire monitoring and modelling are necessary civic responsibilities.

In Part III, which deals with applications of spatial modelling to urban system dynamics, Stuart Barr and Mike Barnsley demonstrate the utility of built-form connectivity models for characterizing land use in urban systems. This approach uses fine-scale digital map data, derived from remote-sensing data as input to a model. The objective is to infer urban land use from land cover parcel data. The motivation for this research is that with high spatial resolution satellite photography becoming available, such connectivity models might assist the cartographer in estimating land use in a built urban environment from space. The second 'urban' chapter is by Bernard Devereux *et al.* and discusses how a wide range of remote sensing data can be coupled to socio-economic census databases within a GIS to assist with planning policy development. The chapter, therefore, represents the powerful merging of remote sensing, spatial modelling and GIS to a direct societal application. Part IV deals with current challenges and future directions. The penultimate chapter in the book is by Dave Toll and Paul Houser. The contribution deals with land surface modelling in hydrology at large regional scales and represents an intermediate step towards the Earth System Science modelling approaches described briefly above. Large-scale atmospheric and land surface data are assembled from diverse spatial data sources (remote sensing, weather prediction models, ground surface observations, etc.) and integrated, ultimately through formal data assimilation, to generate suites of key hydrological variables that are of great interest to global water cycle modellers and climate modellers. This is a large undertaking that is being conducted at the agency level of US government (i.e. at NASA) and is helping to focus the

ESMF/PRISM initiatives. The chapter is not included in to the hydrological applications Part not because it does not deal with hydrology but because it serves as a practical example of spatial modelling of the terrestrial environment at the 'big science' scale. Furthermore, such a large-scale modelling effort could easily assimilate the examples in all preceding chapters.

In the final chapter, Nick Drake, Stuart Barr and Richard Kelly draw together some of the key strands running through the book and look towards the future of spatial modelling of the terrestrial environment. It is clear that this is a dynamic and diverse research field and that some important issues are beginning to emerge. It is also probable that these issues will affect research modelling strategies in the near future and could have an impact on the way practitioners use remote sensing, GIS and spatial modelling.

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PART I

HYDROLOGICAL APPLICATIONS

Editorial: Spatial Modelling in Hydrology

Richard E.J. Kelly

The simulation and prediction of hydrological state variables have been a significant occupation of hydrologists for more than 70 years. For example, Anderson and Burt (1985) noted that Sherman (1932) devised the unit hydrograph method to simulate location-specific river runoff with a very simple parameterization and data input. Clearly introduced before the availability of high performance and relatively inexpensive computers, this method 'was to dominate the hydrology for more than a quarter of a century, and (is) one which is still in widespread use today' (Anderson and Burt, 1985). The approach is spatial inasmuch as it represents in a 'lumped' fashion upstream catchment processes convergent at the point where runoff is simulated. While the unit hydrograph has been a very useful tool for water resource management, hydrologists have sought to 'spatialize' their methodologies of simulation (and ultimately prediction) to account for variations of catchment processes in two and three spatial dimensions. A primary need to do this has been to be able to represent systems dynamically and especially when a system is affected by an extreme event, such as a flood. Conceptually, this shift towards understanding and accounting for complex hydrological process, has manifested itself in the form of a move towards physically based models and away from simple statistically deterministic models. From the 1980s onwards, and perhaps inevitably, the availability of relatively high performance computers that could undertake vast numbers of calculations has allowed the numerical representation of distributed hydrological processes in a catchment. As a result, the propensity for models to become complex has only been a small step on. Now, complex hydrological models can be executed, in standard 'desktop' computer environments. Furthermore, the challenges facing hydrologists engaged in simulation and prediction are not so much those of technology (although this aspect is constantly pushed forward by ever demanding requirements

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of space and time resolution), but more conceptual and theoretical in nature. For example, given the relatively small technological barriers present, how best should multi-dimensional space and time be represented, in a hydrological model digital environment? How should continuous and real hydrological processes be represented in an artificial grid cell array? Even with the ability to resolve such issues technologically, there are as many different theoretical views concerning the potential solution as there are models on this subject. As Anderson and Bates (2001) note, models are constantly evolving as new theories of hydrological processes mature. Ironically, questions about space and time demonstrate how dynamic the science of hydrology continues to be and how little it has changed from the "unit hydrograph era", when questions of space and time representation were moot.

The implementation of spatial models in hydrology has happened in different ways. Traditionally, models have consisted of some input variable (usually measured in the field, such as precipitation) passed to a transfer function (such as a mass or energy balance equation that could be stochastic or deterministic) which then estimates a state variable (such as stream flow). Models, therefore, can be used to represent hydrological processes or relationships operating within a pre-defined spatial domain. The domain might be a sub-region of a continental region or a river catchment, i.e. a basic hydrological spatial unit. While the 'lumped' spatial model is still used in some instances, many hydrological models attempt to represent explicitly mass or energy transfers discretely within the domain of interest. To do this, it has been customary to consider spatial discretization of the domain in the form of raster and/or vector representation. In the raster representation of continuous space, a model is often applied to all grid cells within a study domain. In this way, even though the model might not be explicitly 'spatial', the fact that it represents the average or dominant processes operating over a spatial area (a grid cell) implies spatiality. In other forms, distributed process models explicitly account for the spatial relationship between adjacent cells and are explicitly 'spatial' in character (for example, a runoff routing in a river catchment). Raster grid representations can take many different forms including triangles, rectangles, hexagons, etc. They can also be defined in three-dimensional space in the form of voxels, although the rectangular grid (square) is the most commonly used form. Vector representations of space consist of points, lines and polygon shapes with attributes associated with each element. The hydrological model is applied to the region bounded by polygons and represents the processes operating therein. In most respects, the implementation of models in hydrology is applied using raster representation. However, as Beven (2003) notes "... it is often inappropriate to force an environmental problem into a raster straitjacket" and the future for distributed hydrological modelling is far from clear. Nevertheless, the raster representation is a convenient form of coupling remote sensing data to models since remote-sensing data usually represent instantaneous fields of view as recorded by the observing instrument. In this Part, therefore, we examine how remote sensing data can be used with spatial models in hydrology.

Remote sensing products are coupled to hydrological models in different ways. They might be used to drive the hydrological catchment model or a land surface model (LSM) directly or they might be combined with model-estimated geophysical state variable to produce a "best estimate" via a filter. Figure E1 shows a generalized summary of the approach, which by no means covers all possibilities. Typically, remote sensing data are transformed into an estimated hydrological state variable (product) via a retrieval algorithm that can use physically based or empirical sub-models. Many algorithms are complex and require ancillary spatial data, such as topographical or meteorological data, to produce the required

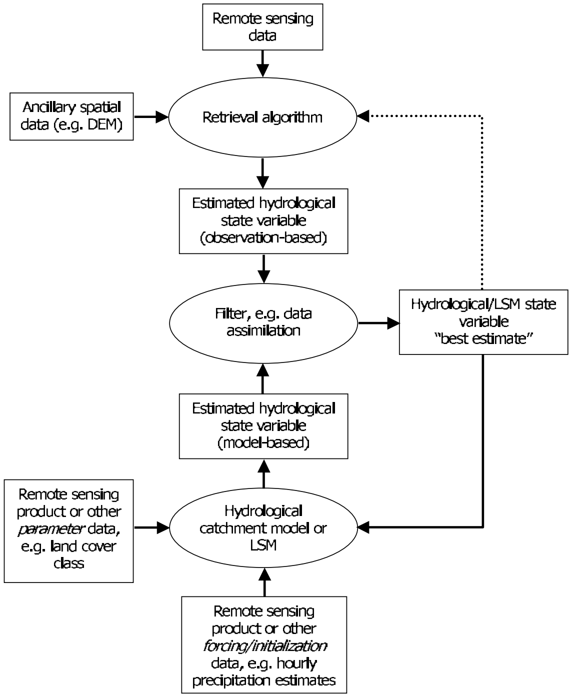

Figure E1 *Generalized view of the coupling of remote sensing data with land-based models in hydrology.*

geophysical state variable. In the early development of remote sensing applications, algorithms were often simple in scope (e.g. a simple statistical classification algorithm), but with increased understanding of the interaction between electromagnetic radiation and hydrological state variables, algorithms have generally improved, albeit often with an increase in algorithm complexity. There are always errors associated with derived remote sensing products. For operational applications, these are usually (or should be) well defined. For research purposes, however, the uncertainties may be less well defined and, therefore, can be the root cause of error propagation through the coupled model to the estimated state variable. Only by thorough model verification and testing procedures can the errors be fully specified and reduced.

The remote-sensing product (estimated hydrological state variable) can be passed directly to the hydrological model in the form of a model parameter (e.g. land cover class), as a model forcing variable (e.g. hourly precipitation) or as an initial state variable (e.g. soil moisture). It is usually only one of several parameters of forcing/initialization variables. When there is large uncertainty associated with the hydrological model estimates, it has been shown that by combining the model-based estimates with observation-based estimates, hybrid "best estimates" can be derived. This combination is often achieved through a "filter", such as data assimilation, which typically computes the best estimate of the hydrological state variable as a weighted average of the model-based and remote sensing-based state estimates. The weighting is determined from the error attributed to the model-based and remote sensing-based hydrological state variable estimates; more weight is given to the estimates with smaller associated error. A best estimate can be used to re-initialize the hydrological model at the next time step or it might also be used to initialize the remote sensing retrieval algorithm. While Toll and Houser (Chapter 12) demonstrate the use of data assimilation in LSMs, the development of data assimilation applications in hydrology, in general, is still in its infancy. For an account of its more mature application in the atmospheric sciences, Kalnay (2002) provides a good explanation of how data assimilation is used in numerical weather prediction. There are alternative filter methodologies that can be used to combine observation-based and model-based estimates and these include spatial or temporal interpolation.

In the following four chapters different specific applications are described that couple remote sensing with spatial hydrological models, in different ways. In Chapter 2, Bamber describes how the Antarctic ice sheet dynamics can be modelled, using satellite-derived topography estimates. In this example, the remote-sensing product is used as a driving parameter in physically based models of ice flow. He shows that the accuracy of the altimeter-based ice sheet elevation estimates affects the modelled estimates of ice flow, which is a key component in calculating the mass balance of Antarctica. The chapter by Kelly *et al.* (Chapter 3) analyzes and compares spatial variations of global ground-measured snow depth with satellite passive microwave estimates of snow depth. Since satellite estimates are areal in nature, while ground measurements tend to be representative of a point, the spatial scaling between these types of estimates is uncertain. For example, how far are the point measurements representative of wider areal variations in snow depth? The chapter also summarizes recent and current approaches for satellite passive microwave observations of snow depth and SWE. Burke *et al.* (Chapter 4) demonstrate how coupled land surface and microwave emission models can help with the estimation of soil moisture. The chapter describes how passive microwave soil moisture estimates can be assimilated into a state-of-the-art land surface model (LSM). They recognize the shortcomings of LSMs and suggest that improvements in model physics and improved parameterization of soil moisture heterogeneity in the pixels would improve the estimates of soil moisture and, therefore, improve the performance of the LSM. Finally, in Chapter 5, Bates *et al.* illustrate how high spatial resolution LiDAR and synthetic aperture radar (SAR) products can be used for flood inundation simulation. Interestingly, they suggest that the future of many spatially distributed modelling frameworks will rely on remote sensing data, that are better specified in terms of the accuracy of the derived hydrological variable.

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2

Modelling Ice Sheet Dynamics with the Aid of Satellite-Derived Topography

Jonathan L. Bamber

2.1 Introduction and Background

The Greenland and Antarctic ice sheets contain about 80% of the Earth's freshwater, and cover 10% of the Earth's land surface. They play an important role in modulating freshwater fluxes into the North Atlantic and Southern Ocean, and if they were to melt completely they would raise global sea level by around 70 m. Thus, even a relatively small imbalance in their mass budget has a significant influence on global sea level changes. The current rate of sea level rise is $\sim$2 mm a^{-1}. About half of this can be accounted for through the melting of sub-polar glaciers and thermal expansion of the oceans. The other half, however, is unaccounted for and it seems likely that the Greenland and/or Antarctic ice sheets are responsible. The uncertainty in their mass budget is, however, equivalent to the total sea level rise signal of 2 mm a^{-1}. To reduce this uncertainty, and to improve our ability to model future changes, accurate measurements of the form and flow of the ice sheets are essential.

The over-arching rationale for studying the ice sheets is often limited to their influence on sea level as there is a clear cause and effect and it is one of the key issues associated with global warming. It is important to note, however, that the ice sheets also have a fundamental impact on the climate system in other ways. In particular, they are primary sources of freshwater fluxes into the North Atlantic and Southern Oceans. Changes in these fluxes could have, for example, a profound impact on the thermohaline circulation of the North Atlantic. Such changes have been associated with rapid climate change during the last

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glacial period (Manabe and Stouffer, 1993). The existence of the Antarctic ice sheet greatly reduces absorption of solar radiation as the albedo of dry snow is about 0.9 compared to 0.01 for open ocean. This is known as the ice-albedo positive feedback, which maintains lower temperatures through the high albedo of snow. This feedback mechanism is one of the reasons why the polar regions are believed to be more sensitive to global warming than lower latitude areas (Hougton, 1996).

The ice sheets interact and influence several components of the climate system and to model these interactions accurately, we need to be able to accurately model the behaviour of the ice sheets. Here, we present an overview of this modelling activity and how, accurate ice sheet topography has been used as an input to, and validation of, the models.

Satellite remote sensing is the tool of choice for studying an area as remote, hostile, expensive to operate in, and as large as the Antarctic ice sheet (AIS), which covers an area of some 13 M km^2 (greater than the conterminus USA). Although the Greenland ice sheet (GrIS) is about ten times smaller and more accessible, satellite remote sensing still plays a key role in observing and monitoring its behaviour. As a consequence, two space agencies have both recently initiated programmes whose primary focus is observations of the cryosphere (NASA with the Ice, Cloud and Land Elevation Satellite (ICESat) and ESA with CryoSat).

2.1.1 The Relevance of Topography

In hydrological modelling, accurate topography is probably *the* most important boundary condition. In the case of ice sheets, the link is perhaps less obvious but equally important. Ice sheet topography is an important parameter in numerical modelling for two reasons. First, it can be used to validate the ability of a model to reproduce the present-day geometry. Second, as with water, ice flows downhill (over an appropriate length scale) and the magnitude of the gravitational driving force that creates this flow is proportional to the surface slope (Figure 2.1). To accurately reproduce the dynamics of an ice sheet a model must, therefore, accurately reproduce surface slope or use it as an input boundary condition.

The gravitational driving force, τ, can be approximated by:

$$\tau = \rho g h \alpha \tag{1}$$

for small bed slopes, where ρ is ice density, g is gravity, h is ice thickness and α is

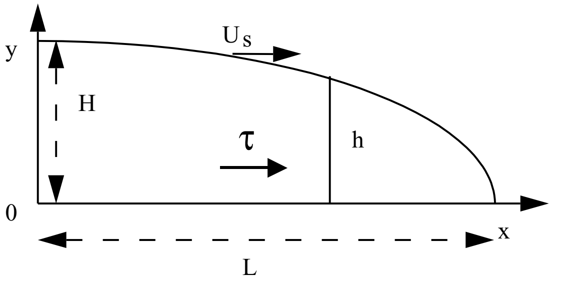

Figure 2.1 *Schematic diagram of an ice sheet showing the relationship between driving stress and slope*