Programme Summary for:

Studying Uncertainty in Palaeoclimate Reconstructions: A Network (SUPRA-net)

A. Context and aim of the programme

Understanding past climate variability is a key component in predicting future climate change with uncertainty being the main obstacle. Indeed, it is of such importance that a whole chapter is devoted to *Palaeoclimate* in the 2007 report by the International Panel for Climate Change (IPPC) [1]. The authors conclude e.g. that "During the last glacial period, abrupt regional warmings (probably up to 16°C within decades over Greenland) occurred repeatedly over the North Atlantic region" (Exec Summary, p. 435). Uncertainty is a major theme in the chapter with the words 'likely' and 'certain' occurring over 120 times in its 66 pages. It emphasises the need for sources of information to be "integrated wherever possible to reduce uncertainty in the assessment". Its concluding section is on "Key Uncertainties". SUPRA-net is a statistician-led, international, interdisciplinary team focused on such uncertainties.

Reconstructions of past climate are based on analyses of e.g. lake, ice, peat and cave deposits. Proxy data are measurements on the chemistry of these deposits or on indicative remnants of fossil plant/animal remains found in them. Typically these are available in sets of 100+ samples from a core, irregularly spanning the past 10 to 15,000 years. Such data form the basis of quantitative, but uncertain, reconstruction of aspects of palaeoclimate, e.g. mean annual temperature; we know very little about the nature and scale of these uncertainties. Consequently it is difficult to evaluate the global circulation models (GCMs, based on fluid dynamical, chemical, and biological equations) that are used to predict climate change (e.g. [1], [2], [3], [4], [5] and on-going work [6] and [7]). SUPRA-net will focus on uncertainty in palaeoclimate reconstruction. In point of fact, understanding and reducing uncertainty about palaeoclimate is, for us, more important than reconstruction *per se*.

Integrating proxy data—and their uncertainties—is the specific technical challenge of SUPRA-net. Tools for regional palaeoclimate reconstruction must be able to 'borrow strength' from multiple proxy types and multiple locations in space and time, relying not only on information from a single data set, but using the most informative aspects of several. They should also be able to quantify uncertainty on all aspects of both the proxy-data (inputs) and the palaeoclimate reconstructions (outputs). Despite the fact that multi-proxy climate reconstruction has been the stated goal of several recent projects (e.g. [8], [9] [10], [11], [12], [13]), such tools do not yet exist. The ultimate aim of SUPRA-net is tailored statistical modelling tools that will yield palaeoclimate reconstructions based on multiple proxies—making due allowance for all relevant sources of uncertainty—thus making it possible to integrate them with GCMs. This aim is unique; PalaeoQUMP [7], by contrast, seeks to use variability in published palaeodata, uncertainties on which are typically not quantified, to aid GCM-based climate prediction.

It is now clear that the statistical framework most suited to achieving our aim is that of Bayesian hierarchical modelling. Over more than a decade Buck and co-workers have demonstrated the power of this approach in archaeology; particularly for integrating groups of related radiocarbon dates [14, 15, 16, 17, 18, 19, 20, 21, 22, 23]. Such methods have relevance in proxy-based palaeoclimate science too, where radiocarbon dating uncertainties can be of the order of a century or more. Haslett and co-workers have recently shown that the Bayesian approach extends to studying the palaeoclimate of an entire core; making due allowance for uncertainties in the proxy measurements, their relationship to climate and the true calendar dates of samples

implied by their depths. They have resolved several of the technical, computational, difficulties and have shown that Bayesian models can, in principle, be used for the type of multi-proxy, multi-core, space-time integration called for by IPCC [24, 25, 26, 27, 28] (ongoing thanks to SFI funding). Nychka and co-workers have developed Bayesian models for several kinds of complex geophysical datasets and have recently used modern computational methods to help to quantify uncertainty in paleoclimate reconstructions [29] (ongoing thanks to NSF funding). Several proxy specialists (e.g. Huntley and co-workers with pollen [24] and Korhola and colleagues with chronimids [30, 31, 32]) already have collaborations with specialists in Bayesian modelling. The case studies arising from these collaborations are compelling. Consequently, proxy experts have enthusiastically joined SUPRA-net, seeking help from Bayesian statisticians to quantify data collection uncertainties, both *post hoc* and in planning future work. Buck's work on the Leverhulme funded IntCal project has ideally prepared her to lead a group of statisticians to offer such support. On IntCal, she helped more than twenty radiocarbon scientists to quantify uncertainty on a range of data types prior to building tailored models that were used to construct the 2004 internationally-agreed radiocarbon calibration curves [33, 34, 35, 36] (ongoing thanks to NERC funding). For these and other reasons (given in Section C below) the time is now right for Bayesian statisticians to collaborate with palaeoclimate scientists and global circulation modellers (who are typically not statisticians) to allow cutting edge statistical methods to be more widely adopted in this area of scientific endeavour.

The interdisciplinary SUPRA-net team brings together experts active in cognate international projects QUEST [37], PIMP2 [6] and PalaeoQUMP [7]) and several research teams, lead by researchers at various career stages (core group ages are from 37 to 59) who will be encouraged to involve their younger members. Its work will be undertaken in two phases. In the first, a 30 delegate 'melting pot' workshop will lead to a position paper for a major journal such as *Quaternary Science Reviews*. In the second we will submit, to major national and international research funding bodies, several over-lapping funding applications on themes arising from phase one. See Section D (below) for details.

B. Summary of the expertise contributed by core institutions

See also Staff Schedule and CVs of principal partners.

University of Sheffield, UK

Department of Probability and Statistics

Bayesian statistics, particularly as applied to archaeo- and palaeo-research and large and complex models of real world problems. Home to BCal; web-based software for Bayesian radiocarbon calibration.

Department of Geography

Quaternary palaeoenvironments, aeolian landscapes, palaeoclimate reconstruction, luminescence dating.

Trinity College Dublin, Ireland

Department of Statistics

Statistics with particular interest in palaeoclimate reconstruction, modelling spatial and temporal variation and high performance computing methods for implementing such models.

Queen's University Belfast, UK

Centre for Chronology, Environment and Climate Change, Department of Archaeology and Palaeoecology

Studies of past climate and environmental change using a range of terrestrial proxies (tree-rings, coleoptera, pollen, plant macro-fossils, etc) and chronological methods (radiocarbon dating, dendrochronology, tephrochronology). Responses of individual proxies to a range of climate and ecological conditions/processes.

Frontier Research Center for Global Change, Yokohama City, Japan

Global Warming Research Programme

Quantitative projection of global warming. Home to a Palaeoclimate Research Group focussing on palaeoclimate modelling and data assimilation; probabilistic estimation of future climate; modelling uncertainty in climate predictions.

National Center for Atmospheric Research, Boulder, USA

Home to researchers from a wide range of backgrounds relevant to the proposed project including: future and palaeoclimate simulation, whole earth system modelling, study of past climates using proxy data including tree-rings, ice core data, and lake and ocean cores.

Durham University, UK

Department of Archaeology

Statistical models for age-depth relationships and Bayesian analyses of data from a range of chronometric dating techniques.

School of Biological and Biomedical Sciences

The relationship between environmental change and changes in the distributions of organisms and the composition, structure and dynamics of ecosystems; especially biospheric feedbacks to the climate system.

Statistics Group, Department of Mathematical Sciences

Uncertainty analysis for large-scale physical models in particular GCMs.

University of Helsinki, Finland

Environmental Change Research Unit

Development and application of hydrobiological, palaeoecological and computational techniques to provide historical perspectives on ecological and environmental change. Particular expertise in palaeolimnology, palaeoecology, and microfossil analysis.

C. Significance of the programme

The goals outlined above cannot be achieved without genuine interdisciplinary collaboration of the kind and scale proposed here (i.e. including a much larger number of partners from a wider range of backgrounds than any project currently underway).

SUPRA-net is timely because of recent developments in the disciplines involved.

1. There is increased interest in the GCM community to use understanding of the variability in past climate to improve statements about uncertainty on future climate predictions (e.g. [38], [39] and on-going projects [6] and [7]).

2. Following the considerable success of Buck and colleagues in developing tailored Bayesian chronology building tools for archaeologists [14, 15, 16, 17, 18, 19, 20, 21, 22, 23], there is growing interest in such methods in the palaeoclimate community [40, 41, 42].

3. Bayesian modelling for palaeoclimate reconstruction clearly has lots to offer [24, 30, 31, 32, 43] and recent work shows that associated computational challenges can be overcome [27, 44].

4. Concerns in the palaeoenvironment research community about inadequate handling of uncertainty in proxy-based reconstruction, articulated sporadically for sometime, are increasing [12, 42, 45, 46, 47, 48, 49].

D. Description of arrangements for interchange

Building on experience gained by Buck while a member of the Leverhulme funded IntCal Network, we plan the work of SUPRA-net in two phases.

In Phase One, 30 delegates (see Staff Schedule for a list) will attend a 'melting pot' workshop so that we can document the uncertainties associated with a range of different terrestrial climate proxies and propose a detailed framework in which to formalise their joint uncertainty. This will **not** be an ordinary research workshop; it will be a series of interactive discussions focusing on sources of uncertainty in each data source. Each session will have a statistician allocated who will act as facilitator, leading discussion on finding ways to help quantify, handle and model the uncertainties identified. One of our objectives in coming together in this way is to allow members of the network to share one anothers' skills-base; building firm bridges between the somewhat disparate research communities will be vital to the success of what is to follow. The output from this first phase will be a position paper (for a journal such as *Quaternary Science Reviews*) to which all 'melting pot' delegates will contribute with support of a Network Facilitator (see Staff Schedule).

Phase Two will involve building new collaborative teams to write several (about 4) major funding proposals in order that (after the end of Leverhulme funding) we can tackle the most important research issues identified in Phase One. The core members of the network will take the academic lead, but they will be supported by the Network Facilitator (see Staff Schedule). Likely topics for the funding proposals include: quality and uncertainty issues in specific proxies; temporal modelling for long palaeoenvironmental records; spatio-temporal modelling for palaeoclimate reconstruction; assimilation of palaeoenvironmental data into GCMs. Likely sources of funding for such proposals (depending on the country of origin of the PI and the make-up of the teams) are: research councils in individual countries (e.g. NERC, EPSRC, SFI, NSF, etc), charitable trusts (e.g. Leverhulme Trust) and international research funding agencies such as ESF and FP7.

E. Why the Leverhulme Trust is the most appropriate funder

The Leverhulme Trust is well known for its encouragement of interdisciplinary research and our proposed project crosses so many disciplinary boundaries that we see the Trust as the natural place to seek support for our work. SUPRA-net brings together experts from disciplines that are currently working on closely related issues, but are not interacting as much as they might. In so doing, we seek to encourage the transfer of methods and ideas of 'best practice' between disciplines and to reduce redundancy of effort in the wider research community. The breadth of expertise of those contributing to this project means that it does not fit well into the remit of any of the UK research councils. This along with the general shortage of funding elsewhere for network-type projects means that the Leverhulme Trust seems the ideal funding agency for this work.

References

[1] E. Jansen, J. Overpeck, K.R. Briffa, J.-C. Duplessy, F. Joos, V. Masson-Delmotte, D. Olago, B. Otto-Bliesner, W.R. Peltier, S. Rahmstorf, R. Ramesh, D. Raynaud, D. Rind, O. Solomina, R. Villalba, and D. Zhang. Palaeoclimate. In S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller, editors, *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, pages 433–497. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2007.

[2] J. H. E. Wright, J. E. Kutzbach, T. Webb III, W. F. Ruddiman, F. A. Street-Perrott, and P. J. Bartlein. *Global Climates since the Last Glacial Maximum.* University of Minnesota Press, Minneapolis, 1993.

[3] I. Farrera, S. P. Harrison, I. C. Prentice, G. Ramstein, J. Guiot, P. Bartlein, R. Bonnefille, M. Bush, W. Cramer, U. von Grafenstein, K. Holmgren, H. Hooghiemstra, G. Hope, D. Jolly, S. E. Lauritzen, Y. Ono, S. Pinot, M. Stute, and G. Yu. Tropical climates at the last glacial maximum: a new synthesis of terrestrial palaeoclimate data. I, Vegetation, lake levels and geochemistry. *Climate Dynamics*, 15:823–856, 1999.

[4] S. Joussaume, K. E. Taylor, P. Braconnot, J. F. B. Mitchell, J. E. Kutzbach, S. P. Harrison, I. C. Prentice, A. J. Broccoli, A. Abe-Ouchi, P. J. Bartlein, C. Bonfils, B. Dong, J. Guiot, K. Herterich, C. D. Hewitt, D. Jolly, J. W. Kim, A. Kislov, A. Kitoh, M. F. Loutre, V. Masson, B. McAvaney, N. McFarlane, N. de Noblet, W. R. Peltier, J. Y. Peterschmitt, D. Pollard, D. Rind, J. F. Royer, M. E. Schlesinger, J. Syktus, S. Thompson, P. Valdes, G. Vettorett, R. S. Webb, and U. Wyputta. Monsoon changes for 6000 years ago: results of 18 simulations from the Paleoclimate Modeling Intercomparison Project (PMIP). *Geophysical Research Letters*, 26:859–862, 1999.

[5] K. E. Kohfeld and S. P. Harrison. How well can we simulate past climates? Evaluating the models using global palaeoenvironmental datasets. *Quaternary Science Reviews*, 19:1–5, 2000.

[6] Palaeoclimate Modelling Intercomparison Project Phase II. `http://pimp2.lsce.ipsl.fr`.

[7] Using Palaeodata to Reduce Uncertainties in Climate Prediction. `http://www.bridge.bris.ac.uk/projects/PalaeoQUMP`.

[8] B. Ammann, H.J.B. Birks, S. J. Brooks, U. Eicher, U. von Grafenstein, W. Hofmann, G. Lemdahl, J. Schwander, K. Tobolski, and L. Wick. Quantication of biotic responses to rapid climatic changes around the Younger Dryas a synthesis. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 159:313–347, 2000.

[9] H. H. Birks, R.W. Battarbee, H.J.B. Birks, and contributors. The development of the aquatic ecosystem at Krakenes Lake, western Norway, during the late-glacial and early-Holocene a synthesis. *Journal of Paleolimnology*, 23:91–114, 2000.

[10] A. E. Viau, K. Gajewski, P. Fines, D. E. Atkinson, and M. C. Sawada. Widespread evidence of 1500 yr climate variability in North America during the past 14,000 yr. *Geology*, 30:455–458, 2002.

[11] B. A. S. Davis, S. Brewer, A. C. Stevenson, J. Guiot, and Data Contributors. The temperature of Europe during the Holocene reconstructed from pollen data. *Quaternary Science Reviews*, 22:1701–1716, 2003.

[12] H. H. Birks and J. B. Birks. Multi-proxy studies in palaeolimnology. *Vegetation History and Archaeobotany*, 15:235–251, 2006.

[13] K. Gajewski, A. E. Viaul, M. Sawada, D. E. Atkinson, and P. Fines. Synchronicity in climate and vegetation transitions between Europe and North America during the Holocene. *Climatic Change*, 78:341–361, 2006.

[14] C. E. Buck, J. B. Kenworthy, C. D. Litton, and A. F. M. Smith. Combining archaeological and radiocarbon information: a Bayesian approach to calibration. *Antiquity*, 65:808–821, 1991.

[15] C. E. Buck, C. D. Litton, and A. F. M. Smith. Calibration of radiocarbon results pertaining to related archaeological events. *Journal of Archaeological Science*, 19:497–512, 1992.

[16] C. E. Buck, C. D. Litton, and S. J. Shennan. A case study in combining radiocarbon and archaeological information: the early Bronze Age settlement of St. Veit-Klinglberg, Land Salzburg, Austria. *Germania*, 72:427–447, 1994.

[17] C. E. Buck, C. D. Litton, and E. M. Scott. Making the most of radiocarbon dating: some statistical considerations. *Antiquity*, 68:252–263, 1994.

[18] C. E. Buck, J. A. Christen, J. B. Kenworthy, and C. D. Litton. Estimating the duration of archaeological activity using ^{14}C determinations. *Oxford Journal of Archaeology*, 13:229–240, 1994.

[19] C. E. Buck, W. G. Cavanagh, and C. D. Litton. *The Bayesian Approach to Interpreting Archaeological Data*. Wiley, Chichester, 1996.

[20] J. A. Zeidler, C. E. Buck, and C. D. Litton. The integration of archaeological phase information and radiocarbon results from the Jama River Valley, Ecuador: a Bayesian approach. *Latin American Antiquity*, 9(2):135–159, 1998.

[21] C. D. Litton and C. E. Buck. An archaeological example: radiocarbon dating. In S. Richardson W. Gilks and D. Spiegelhalter, editors, *Markov Chain Monte Carlo in Practice*, pages 465–480. Chapman and Hall, London, 1996.

[22] P. G. Blackwell and C. E. Buck. The Late Glacial human reoccupation of north western Europe: new approaches to space-time modelling. *Antiquity*, 77(296):232–240, 2003.

[23] C. E. Buck and A. R. Millard. *Tools for Constructing Chronologies: crossing disciplinary boundaries*. Springer-Verlag, London, 2004.

[24] J. Haslett, M. Whiley, S. Bhattacharya, M. Salter-Townshend, S. P. Wilson, J. R. M. Allen, B. Huntley, and F. J. G. Mitchell. Bayesian palaeoclimate reconstruction. *Journal of the Royal Statistical Society: Series A*, 169:395–438, 2006.

[25] J. Haslett, A. Parnell, and M. Salter-Townsend. Modelling temporal uncertainty in palaeoclimate reconstructions. *Proceedings of the 21st International Workshop on Statistical Modelling*, pages 26–37, 2006.

[26] M. Salter-Townsend and J. Haslett. Modelling zero inflation of compositional data. *Proceedings of the 21st International Workshop on Statistical Modelling*, pages 448–456, 2006.

[27] J. Haslett, A. Parnell, and M. Salter-Townsend. Space-time models for reconstructing the European palaeoclimate. *Bulletin of the 56th Session of the International Statistical Institute*, 2007. to appear.

[28] J. Haslett and A. Parnell. Monotone smoothing: application of a compound Poisson-Gamma process to modelling radiocarbon-dated depth chronologies. *submitted*, 2007.

[29] B. Li, C. Ammann, and D.Nychka. The Hockey Stick and the 1990s: a statistical perspective on reconstructing hemispheric temperatures. *Tellus*, 2007. In press.

[30] K. Vasko, H. T. Toivonen, and A Korhola. A Bayesian multinomial Gaussian response model for organism-based environmental reconstruction. *Journal of Paleolimnology*, 24:243–250, 2000.

[31] H. T. T. Toivonen, H. Mannila, A. Korhola, and H. Olander. Applying Bayesian statistics to organism-based environmental reconstruction. *Ecological Applications*, 11:618–630, 2001.

[32] A. Korhola, K. Vasko, H. Toivonen, and H. Olandor. Holocene temperature changes in northern Fenno-scandia reconstructed from chironomids using Bayesian modelling. *Quaternary Science Reviews*, 21:1841–1860, 2002.

[33] C. E. Buck and P. G. Blackwell. Formal statistical models for estimating radiocarbon calibration curves. *Radiocarbon*, 46(3):1093–1102, 2004.

[34] P. J. Reimer, M. G. L. Baillie, E. Bard, A. Bayliss, J. W. Beck, C. J. H. Bertrand, P. G. Blackwell, C. E. Buck, G. S. Burr, K. B. Cutler, P. E. Damon, R. L. Edwards, R. G. Fairbanks, M. Friedrich, T. P. Guilderson, A. G. Hogg, K. A. Hughen, B. Kromer, McCormac G., S. Manning, C. B. Ramsey, R. W. Reimer, S. Remmele, J. R. Southon, M. Stuiver, S. Talamo, F. W. Taylor, J. van der Plicht, and C. E. Weyhenmeyer. IntCal04—terrestrial radiocarbon age calibration, 0–26 cal kyr BP. *Radiocarbon*, 46(3):1029–1058, 2004.

[35] K. A. Hughen, M. G. L. Baillie, E. Bard, J. W. Beck, C. J. H. Bertrand, P. G. Blackwell, C. E. Buck, G. S. Burr, K. B. Cutler, P. E. Damon, R. L. Edwards, R. G Fairbanks, M. Friedrich, T. P. Guilderson, B. Kromer, G. McCormac, S. Manning, C. B. Ramsey, P. J. Reimer, R. W. Reimer, S. Remmele, J. R. Southon, M. Stuiver, S. Talamo, F. W. Taylor, J. van der Plicht, and C. E. Weyhenmeyer. Marine04—marine radiocarbon age calibration, 0–26 cal kyr BP. *Radiocarbon*, 46(3):1059–1086, 2004.

[36] F. G. McCormac, A. G. Hogg, P. G. Blackwell, C. E. Buck, T. F. G. Higham, and P. J. Reimer. SHCal04—Southern Hemisphere calibration, 0–11.0 cal kyr BP. *Radiocarbon*, 46(3):1087–1092, 2004.

[37] Quantifying and Understanding the Earth System. `http://quest.bris.ac.uk/`.

[38] J. D. Annan, J. C. Hargreaves, R. Ohgaito, A. Abe-Ouchi, and S. Emori. Efficiently constraining climate sensitivity with ensembles of paleoclimate simulations. *SOLA*, 1:181–184, 2005.

[39] J. D. Annan and J. C. Hargreaves. Using multiple observationally-based constraints to estimate climate sensitivity. *Geophysical Research Letters*, 2006. L06704, doi:10.1029/2005GL025259.

[40] J. A. Christen, R. S. Clymo, and C. D. Litton. A Bayesian approach to the use of ^{14}C dates in the estimation of the age of peat. *Radiocarbon*, 37:431–442, 1995.

[41] M. Blaauw and J. A. Christen. Radiocarbon peat chronologies and environmental change. *Applied Statistics*, 54:805–816, 2005.

[42] M. Blaauw, J. A. Christen, D. Mauquoy, J. van der Plicht, and K. D. Bennett. Testing the timing of radiocarbon-dated events between proxy archives. *The Holocene*, 17:283–288, 2007.

[43] Panu Erästö and Lasse Holmström. Selection of prior distributions and multiscale analysis in Bayesian temperature reconstructions based on fossil assemblages. *Journal of Paleolimnology*, 36:69–80, 2006.

[44] F. Lindgren and H. Rue. Explicit construction of GMRF approximations to generalised Matérn fields on irregular grids. Preprints in Mathematical Sciences 2007:12, Centre for Mathematical Sciences, Lund Institute of Technology, Lund University, 2007.

[45] M. Blaauw, J. A. Christen, D. Mauquoy, J. van der Plicht, and K. D. Bennett. 21st century suck-in or smear: testing the timing of events between archives. *PAGES News*, 14(3):15–16, 2006.

[46] K. D. Bennett. Confidence intervals for age estimates and deposition times in late-Quaternary sediment sequences. *The Holocene*, 4:337–348, 1994.

[47] K. D. Bennett. Comment: the Greenland 8200 cal. yr BP event detected in loss-on-ignition profiles in Norwegian lacustrine sediment sequences. *Journal of Quaternary Science*, 17:97–99, 2002.

[48] E. Heegaard, A.F. Lotter, and H.J.B. Birks. Aquatic biota and the detection of climate change: are there consistent aquatic ecotones? *Journal of Paleolimnology*, 35:507–518, 2006.

[49] G. van der Schrier, T.J. Osborn, K.R. Briffa, and E.R. Cook. Exploring an ensemble approach to estimating skill in multiproxy palaeoclimate reconstructions. *The Holocene*, 17:119–129, 2007.