Reference Number: (to be added by Directorate)

British Antarctic Survey

APPLICATION FOR A RESEARCH PROJECT

This form should be filled in on the screen and e-mailed to Dougal Goodman. The tables will expand to accommodate additional text as required. The forms will be handled electronically; do not be concerned about page breaks.

1.1 Proposer(s)

	E-mail	Signature	Date
Project Leader	d.vaughan@bas.ac.uk DGV		19/11/98
Principal Investigator (for baseline programmes)	d.vaughan@bas.ac.uk DGV		19/11/98

1.2 Approval

	Signature	Date
Approved for external review by the Director, BAS		

1.3 Consultation

List names of senior staff consulted in the preparation of this proposal	Dr R Mulvaney, Prof. EM Morris, Dr CSM Doake, Dr RCA Hindmarsh, Dr BC Storey, J Hall.

2.1 Title (maximum 200 characters)

Basin Balance Assessment and Synthesis
(GIANTS-BBAS)

2.2 Keywords

Ice, ice dynamics, mass balance, sea-level, glaciology, radar, gravity, magnetics, airborne survey, accumulation, ice core, ice stream, Pine Island Glacier, Thwaites Glacier, Amundsen Sea

2.3 Project Type (Enter Value)

Baseline Project 1, Independent Project 2, Commissioned Research Project 3:

1

Enter 1 in this box if there is a link between this project and a potential Antarctic Funding Initiative bid:

2.4 Baseline Programme Title (if linked to Baseline Programme)

Global Interactions of the ANTarctic Ice Sheet (GIANTS)

3 Abstract (maximum 750 characters)

We propose to measure the mass-balance of two key basins in the West Antarctic Ice Sheet, those feeding Pine Island and Thwaites glaciers. These have been predicted to be the most likely site to initiate major change and have already been shown to be undergoing decadal change. Data we collect will allow the us to determine the mode of change and whether the cause is; precipitation change, ice-sheet instabilities ice-ocean processes or ice-divide migration. Details of fieldwork will be finalised after extensive satellite reconnaissance which, in itself, will advance our understanding of the area. Two elements of fieldwork are envisaged; airborne survey to determine ice and bed characteristics and surface measurements of accumulation-rate variability. Finally, we will implement a basin-scale numerical model of past and future evolution of the ice sheet.

4 Duration

Start Date (month, year 4 digits)	End Date (month, year 4 digits)	Duration (months)
04/2000	03/2005	60

5 Summary of Resources Required

Staff (months)

	Year -1 Apr-Mar	Year 1 Apr-Mar	Year 2 Apr-Mar	Year 3 Apr-Mar	Year 4 Apr-Mar	Year 5 Apr-Mar	TOTAL
BAS Staff	5	33.5	39.5	72.5	56.5	30.5	237.5
Ph D Students	0	0	0	0	0	0	0
Casual Labour	0	2	2	2	3	2	11

Costs (£k)

Capital Costs	8	50.5	30	15	0	0	103.5
Recurrent Costs	2.5	8	34	22	10.5	10	87
TOTAL	10.5	58.5	79	37	10.5	10	190.5

6 Grade of staff required (months)

Grade	Year -1 Apr-Mar	Year 1 Apr-Mar	Year 2 Apr-Mar	Year 3 Apr-Mar	Year 4 Apr-Mar	Year 5 Apr-Mar	TOTAL
Grade 6/7	1	4	5	7	3	1	21
SSO	2	5	8	11	13	5	44
HSO	2	24	26	42	28	24	146
SO	0	0.5	0.5	12.5	12.5	0.5	26.5
Casual labour	0	2	2	2	3	2	11
TOTAL							248.5

7 Recurrent Costs

7.1 Travel and Subsistence £k

	Year -1 Apr-Mar	Year 1 Apr-Mar	Year 2 Apr-Mar	Year 3 Apr-Mar	Year 4 Apr-Mar	Year 5 Apr-Mar	TOTAL
UK	0.5	1	1	2	1	1	6.5
International	2	2	3	3	3	3	16
Antarctic	0	0	0	6	0	0	6
TOTAL	2.5	3	4	11	4	4	28.5

7.2 Other Recurrent Costs (£k)

Item	Year -1 Apr-Mar	Year 1 Apr-Mar	Year 2 Apr-Mar	Year 3 Apr-Mar	Year 4 Apr-Mar	Year 5 Apr-Mar	TOTAL
Commercial storage of cores	0	0	0	0	2	2	4
Ice Core boxes	0	0	0	2	0	2	4
PCs (3-year cycle)	0	2	2	2	2	0	8
PC (Field use)	0	0	3	0	0	0	3
PC peripherals & consumables	0	1	1	1	1	1	5
Training - GPR & GPS	0	0.5	0.5	0	0.5	0	1.5
Software - GPS	0	0	3	0	0	0	3
Software - GPR	0	0	1	0	0	0	1
GPR antenna sledge	0	0.5	0	0	0	0	0.5
Software - Document prep.	0	1	0	1	0	0	2
Software - Airborne radar	0	0	2	0	0	0	2
Reprint / Page Charges	0	0	1	0	1	1	3
Field consumables	0	0	5	5	0	0	10
Field - Batteries	0	0	2	0	0	0	2
Field - generators	0	0	2	0	0	0	2
Field - Airfreight	0	0	4	0	0	0	4
Upkeep of Neutron density probe	0	0	3	0	0	0	3
Field - Packing materials	0	0	0.5	0	0	0	0.5
TOTAL	0	5	30	11	6.5	6	58.5

8 Capital Items (items greater than £3k that have a life longer than 1 year) £k

8.1 Capital Items dedicated to the project

Item	Year -1 Apr-Mar	Year 1 Apr-Mar	Year 2 Apr-Mar	Year 3 Apr-Mar	Year 4 Apr-Mar	Year 5 Apr-Mar	TOTAL
Satellite imagery and data	8	4					12
Unix workstations		12		15			27
TOTAL							39

8.2 Capital Items to be purchased as shared equipment

Item	Year -1 Apr-Mar	Year 1 Apr-Mar	Year 2 Apr-Mar	Year 3 Apr-Mar	Year 4 Apr-Mar	Year 5 Apr-Mar	TOTAL
Ground Penetrating Radar *Only if unavailable from NERC Equipment pool		20*					0
PICO drill		4.5					4.5
Share of upkeep of airborne geophysical survey suite (Amount not known)							0
Upkeep of GPS receivers and software			15				15
Gamma - SAR processing package		30					30
Dielectric profiling system for ice core analysis			15				15
TOTAL							64.5

9 Use of Major Capital Equipment in Cambridge

Item	Year 1 Apr-Mar	Year 2 Apr-Mar	Year 3 Apr-Mar	Year 4 Apr-Mar	Year 5 Apr-Mar	TOTAL
Part use of chemistry cold room				50%		
Unix computing: GIS*						
Unix computing: Image analysis*						
Unix computing: Mass storage*						
Unix computing: Computational resources*						
* - These items are required throughout the project as part of the BAS infrastructure provision						

10 Field and Support Requirements

10.1 Research Station (Months on Station)

From Research Station	Year 1 Apr-Mar		Year 2 Apr-Mar		Year 3 Apr-Mar		Year 4 Apr-Mar		Year 5 Apr-Mar		TOTAL	
	Total Months	No. in party	Total Months	No. in party	Total Months	No. in party	Total Months	No. in party	Total Months	No. in party	Total Months	No. in party
Halley												
Rothera					1	10					1	10
Bird Island												
Signy												
Other (state name)												

Supporting Comments (specify special requirements e.g. laboratory space)

This would comprise two parties; the airborne geophysical party engaged in fitting and testing the Survey Twin Otter (4 scientists, pilot and mechanic) and the oversnow party (2 scientists, 2 FGAs) preparing equipment and field unit. Both parties would be en route to the field, and require laboratory space, and hangar space but will have no special requirements. Since US field operations begin early in the austral summer transit of these personnel will be required at the very beginning of the summer season at Rothera.

The present proposal is based for convenience on oversnow and airborne field campaigns being executed in the same season. While the date of the airborne campaign needs to be agreed with our US collaborators, the oversnow season could potentially be completed in years, 2,3 or 4.

10.2 Scientists in Field (Months and Number of Scientists)

From Research Station	Year 1 Apr-Mar		Year 2 Apr-Mar		Year 3 Apr-Mar		Year 4 Apr-Mar		Year 5 Apr-Mar		TOTAL	
	Total Months	No. in party	Total Months	No. in party	Total Month s	No. in party	Total Months	No. in party	Total Months	No. in party	Total Months	No. in party
Halley												
Rothera					30	6					30	6
Other (state name)												

10.3 Location of Field Parties (enter 1 to show year visited)

Field Party Location Use names from gazetteer or Latitude and Longitude	Year 1 Apr-Mar	Year 2 Apr-Mar	Year 3 Apr-Mar	Year 4 Apr-Mar	Year 5 Apr-Mar
PIG/TG Surface Camp (78^oS 95^oW)			1		
Pine Island Glacier / Thwaites Glacier basins			1		

10.4 Field General Assistants (Months)

Research Station	Year 1 Apr-Mar	Year 2 Apr-Mar	Year 3 Apr-Mar	Year 4 Apr-Mar	Year 5 Apr-Mar	TOTAL
Halley						
Rothera			8			8
Other (state name)						

10.5 Field Units (Units and Vehicles)

From Research Station	Year 1 Apr-Mar		Year 2 Apr-Mar		Year 3 Apr-Mar		Year 4 Apr-Mar		Year 5 Apr-Mar		TOTAL	
	No. Field Units	No. Skidoos or other vehicles	No. Field Units	No. Skidoos or other vehicles	No. Field Units	No. Skidoos or other vehicles	No. Field Units	No. Skidoos or other vehicles	No. Field Units	No. Skidoos or other vehicles	No. Field Units	No. Skidoos or other vehicles
Halley												
Rothera					2	4					2	4
Other (state name)												

10.6 Special Field Equipment

Item	Year -1 Apr-Mar	Year 1 Apr-Mar	Year 2 Apr-Mar	Year 3 Apr-Mar	Year 4 Apr-Mar	Year 5 Apr-Mar	TOTAL
Large work tent (for airborne party)				1			1
Lightweight work tent (for oversnow party)				2			2
Low temperature down clothing				4			4
GPS navigation equipment				4			4
Emergency location beacons				2			2
Fuel sledge				2			2
25 Watt, radio transmitters				2			2
5-m radio antenna				2			2

10.7 Fuel Depots Required (barrels) - Season Put in Place

Location	Year -1 Apr-Mar	Year 1 Apr-Mar	Year 2 Apr-Mar	Year 3 Apr-Mar	Year 4 Apr-Mar	Year 5 Apr-Mar	TOTAL
None required for fieldwork - logistics depot requirement included in 10.11 - 10.13							

10.8 Shiptime (Days including mobilisation time from port for major cruises)

Vessel	Year 1 Apr-Mar	Year 2 Apr-Mar	Year 3 Apr-Mar	Year 4 Apr-Mar	Year 5 Apr-Mar	TOTAL
James Clark Ross						
Bransfield						
HMS Endurance						

Supporting Comments (specify special equipment required on ship e.g. special nets etc.)

We request no ship time be allocated to this project but support the request of GIANTS-RISOC for a cruise in the Amundsen Sea which will complement the aims of this Project.

Recent experience using HMS Endurance and Twin Otters to place fuel at the south of Berkner Island proved highly successful. If a similar exercise were used to place fuel in the Pine Island Glacier / Thwaites Glacier basins the reliance on NSF logistics could be considerably reduced, and perhaps removed entirely. Such an effort could possibly be dovetailed with other projects logistic requirements to reduce overall cost.

10.9 Location of Cruises (enter 1 to show year visited)

Ship Passage Use names from gazetteer or Latitude and Longitude for key way points	Year 1 Apr-Mar	Year 2 Apr-Mar	Year 3 Apr-Mar	Year 4 Apr-Mar	Year 5 Apr-Mar
NONE					

10.10 Technical Support (enter 1 if required and further information will be requested)

Nature of Support	Year -1 Apr-Mar	Year 1 Apr-Mar	Year 2 Apr-Mar	Year 3 Apr-Mar	Year 4 Apr-Mar	Year 5 Apr-Mar
Mechanical			1			
Instrument		1	1			
Computer	1	1	1	1	1	1
Other (state)						

10.11 Twin Otter (hours) - Dedicated

Hours required for survey flying or putting in and retrieving field parties

Ex Research Station	Year 1 Apr-Mar	Year 2 Apr-Mar	Year 3 Apr-Mar	Year 4 Apr-Mar	Year 5 Apr-Mar	TOTAL
Ex Rothera Input of airborne survey team Input oversnow team Survey			60 hours 60 hours 80 hours			
Ex Halley						
Other (state location)						

Supporting Comments (specify special equipment required e.g. radio echo sounding fit)

The complete air support will require two Twin Otters one acting in a deployment role and the other as a survey platform. Fit of airborne geophysical sensors will be required at Rothera. It is likely that an air mechanic will need to accompany the survey aircraft to Pine Island/Thwaites Surface Camp. It is not envisaged that the second Twin Otter will be required to remain at the surface camp during the field campaign but it will also be required for uplift.

Proving flights using the DASH-7 to the blue ice runway at Patriot Hills have been completed and if these become operationally useable then a considerable reduction in deployment hours will be possible

10.12 Twin Otter (hours) - Support

Hours required for depot laying to support survey flights or extend range

Ex Research Station	Year 1 Apr-Mar	Year 2 Apr-Mar	Year 3 Apr-Mar	Year 4 Apr-Mar	Year 5 Apr-Mar	TOTAL
Ex Rothera						
Ex Halley						
Other (state location)						

10.13 Twin Otter (continuous support at field site, days)

Ex Research Station	Year 1 Apr-Mar	Year 2 Apr-Mar	Year 3 Apr-Mar	Year 4 Apr-Mar	Year 5 Apr-Mar	TOTAL
Ex Rothera						
Ex Halley						
Other (state location)			60 PIG/TG Surface Camp			60 PIG/TG Surface Camp

10.14 Dash 7 (hours)

Ex Research Station	Year 1 Apr-Mar	Year 2 Apr-Mar	Year 3 Apr-Mar	Year 4 Apr-Mar	Year 5 Apr-Mar	TOTAL
Ex Rothera			* see 10.11			

Supporting Comments (specify special equipment required e.g. aeromag fit)

The use of Twin Otter for Dash-7 in, depot laying, deployment or field support roles would be entirely acceptable. Specific options are: use blue ice airstrip at Sky-Hi Nunataks as an intermediate depot, use of blue ice airstrip at Patriot Hills as an intermediate depot.

10.15 Other Special Requirements (enter 1 in box if needed in season)

Research Station	Year 1 Apr-Mar	Year 2 Apr-Mar	Year 3 Apr-Mar	Year 4 Apr-Mar	Year 5 Apr-Mar
Hazardous cargo					
Freezer transport			1		
Cool stow			1		
Explosives					
Radioactive samples			1*		
* - Source for Neutron Density Probe (Previously transported and used by BAS in Antarctica)					

If 1 is entered further details will be requested for volumes, maximum temperature etc.

10.16 Health, Safety and Environment

	Enter Y if Yes, N if No	Special risks identified or other comments
Has a risk assessment been carried out?	N	No special risks are anticipated with work in UK No special risks are anticipated with airborne campaign (above those of operating in remote field environment) Oversnow traverse may be beyond BAS's normal search and rescue operation - SAR capability should be maintained from the PIG/TG surface camp or an alternative (e.g. Patriot Hills) - Neutron Density Probe risk assessment has already been completed
Has an environmental impact assessment been undertaken?	N	No adverse environmental impact is anticipated under normal BAS & NSF field operation procedures.

10.17 Data Management Plan

	Enter Y if Yes, N if No	Comments
Will this project generate large data sets which will require special archiving or storage?	Y	AEDC Manager time is included in Question 11
Are there any significant data management issues?	N	Data collected jointly by BAS/NERC and NSF will be subject to a memorandum of understanding to be written at the time of application to NSF.

All NERC supported projects require a data management plan - sufficient resources for the management of data should be included in the proposal.

11 Existing or New Staff Expected to Work on the Project (months)

Name or Post including Ph D students and casual labour	Year -1 Apr-Mar	Year 1 Apr-Mar	Year 2 Apr-Mar	Year 3 Apr-Mar	Year 4 Apr-Mar	Year 5 Apr-Mar	TOTAL
GPS/GPR/Neutron density probe Specialist (Morris / UG6)	0	0	1	6	2	0	9
Senior science adviser (Doake / IMP UG6)	1	4	4	1	1	1	12
Project leader (Vaughan / SSO)	1	3	3	6	3	3	19
Radar scientist and airborne campaign leader (Corr / SSO)	1	2	5	5	10	2	25
Satellite data analyst* (HSO/SSO)	0	12	12	12	0	0	36
Glaciologist (Nath /HSO)	2	12	12	12	12	12	62
Gravity Tech.* (HSO/SSO)	0	0	2	9	5	0	16
Magnetics Tech.* (HSO/SSO)	0	0	0	9	5	0	14
Ice Sheet Modeller* (HSO/SSO)	0	0	0	0	6	12	18
Chemistry Tech.* (SO/HSO)	0	0	0	12	12	0	24
AEDC Database Tech* (SO/HSO)	0	0.5	0.5	0.5	0.5	0.5	2.5
TOTAL	5	33.5	39.5	72.5	56.5	30.5	237.5
* Indicates no present BAS employee identified for this post.							

12 Research Collaboration (HEI or Other Research Body)

Name of Collaborator	Position and Institution Name	Nature of Support or Collaboration
Prof. Duncan Wingham	Professor, University College London	Satellite based reconnaissance of the PIG/TG Basins. (Expertise in SAR imaging and altimetry)
Dr. Don Blankenship	SOAR group leader for ice-sounding radar survey, University of Texas, Austin, USA	Collection and analysis of geophysical data
Dr. Robin Bell	SOAR group leader for magnetics, Lamont Doherty Geophysical Observatory, USA	
Annex A - contains letters of support from the named collaborators with this proposal		

13 Suggested Referees

Name	Full postal address and e-mail
Dr B. Bindschadler	NASA/Goddard Space Flight Center, Code 971, Greenbelt, MD, 20771, USA. bob@igloo.gsfc.nasa.gov
Prof. Richard Alley	Penn State University, Dept. Of Geoscience and Earth System Science, 306 Deike Building, University Park, PA 16802-2711, USA. ralley@essc.psu.edu
Prof. Charles Raymond	University of Washington, Geophysics Program, Box 351650, Seattle, WA, 98195-1650, USA. charlie@geophys.washington.edu
Dr. Ian Allison	Antarctic CRC, University of Tasmania, GPO Box 252C, Hobart 7001, Tasmania, Australia. I.allison@antcrc.utas.edu.au
Dr Hans Oerter	Alfred-Wegener-Institut fur Polar-und-Meersforschung, Postfach 12061, Columbusstrasse, D-27515 Bremerhaven, Germany. Hoerter@awi-bremerhaven.de

Dr. Shridar Anandakrishnan	Penn State University, Dept. Of Geoscience and Earth System Science, 208 Deike Building, University Park, PA 16802-2711, USA. sak@essc.psu.edu
Dr. Stan Jacobs	Columbia University, Lamont-Doherty Earth Observatory, P. O. Box 1000, Rt. 9W., Palisades, NY, USA. sjacobs@ldeo.columbia.edu
Prof. Ian Whillans	Ohio State University, Department of Geological Sciences, 125 South Oval Mall, Columbus, OH, 43210, USA. iwhillan@magnus.acs.ohio-state.edu

14 Related Grants

a. All current NERC research grants.

NERC ref	Brief title	Amount Sought £	Amount awarded £	Dates
GR3/11622	Windborne redistribution of snow: consequences for ice core interpretation (S.D. Mobbs, J.C. King, P.S. Anderson, D.G. Vaughan)	£113 421	£112 719	05/98-04/02
SEED2/12	BEDMAP data management and product generation (D.G. Vaughan and M.R. Thorley)	£60 k	£31.5 k	6/98-9/99

b. All NERC grants which terminated in the last five years

NERC ref	Brief title	Amount sought £	Amount awarded £	Report grading
	NONE			

c. All unsuccessful applications to NERC in the last three years

NERC ref	Brief title	Amount sought £	Dates
	NONE		

d. Any other current applications to NERC

NERC ref	Brief title	Amount sought £	Dates
	NONE		

15 Related Applications to Other Bodies: Successful in the last three years or pending.

Awarding Organisation	Brief title/description	Amount sought £	Amount awarded £	Dates
EU Framework 4	POLAR SNOW - The physical characteristics and properties of snow at the surface of polar ice sheets. ENV4-CT95-0076 (Genthon, Brun, Morris)		£45k	
EU Framework 4	TEMBA - Climate sensitivity of glacier mass balance: the effect of topographic barriers. (Morris, Oerlemans, Kuhn, Bjornsson)		£33k	02/02/97-01/02/98
EU Framework 4	ESAMCA - Satellite altimetry on Filchner-Ronne Ice Shelf. (Doake and others)		$40k	1994-96

16 *Curriculum Vitae* of key individuals who will work on the project (one page of A4 only for each person)

Surname	Forenames	Title
VAUGHAN	David, Glyn	Dr

Does the period of your current post exceed the end date of this proposal? Yes/No. If no give details

No - present FTA ends December, 2000

Degrees and posts held, with dates and any other information which would be of interest to the reviewer.

1981-1984: University of Cambridge (Churchill College). BA (hons) Natural Sciences (Physics).
1984-1985: University of Durham. Full-time M.Sc. in Geophysics. (NERC Advanced Studentship)
1992-1995: Open University. Full-time external Ph.D. Thesis title, *Structural and climatic controls on Antarctic Ice Shelves.* Supervisors, Dr. C.S.M. Doake; Professor D. Sugden, University of Edinburgh.
1986-1998: Glaciologist, Ice and Climate Division, British Antarctic Survey
1998-present: Principal Investigator for Programme: *Global Impacts of Antarctic Ice Sheet*

- Research interests: ice sheet dynamics, ice-sheet/climate interactions
- Five summer seasons in Antarctica engaged airborne and ground-based fieldwork.
- British Association for the Advancement of Science Media Fellow, 1995. (8 week placement to work as a science journalist in the BBC World Service Science Unit)
- Invited speaker at International Arctic Science Committee (IASC) and Scientific Committee on Antarctic Research (SCAR) Symposium (Tromso 1998) on "Sea level & Mass Balance of the Antarctic Ice Sheet"
- Invited participant in the West Antarctic Ice Sheet Initiative. (Washington DC, 1997)
- Prominent role in promoting public awareness in Antarctic and climate science through TV and radio appearances and writing of popular articles.
- Convener of the SCAR Sponsored BEDMAP Project to compile a new bed topography for Antarctica
- Lead author for Third Assessment Report of the Intergovernment Panel on Climate Change 1998-2001.

d. Recent publications (full reference) relevant to the project; if none relevant to the project give other important publications.

(Around 50 Papers, Maps and Reports since 1987)

Vaughan, D. G., H. F. J. Corr and C. S. M. Doake, in press. Distortion of isochronous layers in ice by surface balance variations and non-linear rheology. *Nature*

Vaughan, D. G., 1998. A new classification scheme for ice shelves based on mechanisms of mass gain and loss. Polar Record, 34 (188), 56-58.

Vaughan, D.G. , J.L. Bamber, M. Giovinetto, J. Russell, and A.P.R. Cooper, in press. Reassessment of net surface mass balance in Antarctica. J. Climate.

Smith, A.M. , **D.G. Vaughan**, C.S.M. Doake and A.C. Johnson, in press. Surface lowering of the ice ramp at Rothera Point in response to regional climate change. Ann. Glaciol., **27.**

Vaughan, D.G., and J.L. Bamber, in press. Identifying large-scale areas of damming and rapid flow in the Antarctic Ice Sheet by ERS-1 satellite altimetry. Ann. Glaciol., **27**,

Cattle, H., D. Jenkins and **D.G. Vaughan**, 1997. Sea level and Antarctic Ice Shelf disintegration. The Globe, **36**, 4

Grosfeld, K., H.H. Helmer, M. Jonas, H. Sandhager, M. Schulte and **D.G. Vaughan**, in press. Marine ice beneath Filchner Ice Shelf: evidence from a multidisplinary approach. AGU Antarctic Research Series **75**, 319-339

Jenkins, A., **D.G. Vaughan**, S.S. Jacobs H.H. Helmer and H.J.R. Keys, 1997. Glaciological and oceanographic evidence for rapid melting beneath Pine Island Glacier. J. Glaciol., **43** (143), 114-121.

Vaughan, D.G. and C.S.M. Doake, 1996. Recent atmospheric warming and retreat of ice shelves on the Antarctic Peninsula. Nature **379**, 328-331.

Vaughan, D.G., 1995. Tidal Flexure of Ice Shelves. J. Geophys. Res., **100** (B4), 6213-6224.

Morris, E.M. and D.G. **Vaughan**, 1994. Measurements of surface temperature in West Antarctica. Antarc. Sci., **6** (4), 529-535.

Vaughan, D.G.,1993. Implications for the break up of Wordie Ice Shelf, Antarctica for sea level. Ant. Sci., **5** (4), 403-408.

Vaughan, D.G., D.R. Mantripp, J. Sievers and C.S.M. Doake, 1993. A synthesis of remote sensing data over Wilkins Ice Shelf, Antarctica. Ann. Glaciol., **17**, 211-218.

Vaughan, D.G., 1993. Relating the Occurrence of Crevasses to Surface Strainrate. J. Glaciol., **39**, (132), 255-267.

Doake, C.S.M. and D.G. **Vaughan**, 1991. Rapid Disintegration of Wordie Ice Shelf in Response to Atmospheric Warming. Nature Vol. **350**. No. 6316. pp 328-330.

Surname	Forenames	Title
DOAKE	Christopher, S. M.	Dr

Does the period of your current post exceed the end date of this proposal? Yes/No. If no give details

Yes

Degrees and posts held, with dates and any other information which would be of interest to the reviewer.

1968: B.Sc. (Hons) I; Physics, University of St. Andrews, 1966

1972: Doctor of Philosophy (Physics), University of St. Andrews

Present: Programme leader British Antarctic Survey

- Research interests: ice dynamics, remote sensing, applied to West Antarctic ice sheet
- Twenty three years research experience with BAS since 1973.
- Coordinator, Filchner-Ronne Ice Shelf Programme (FRISP) 1988-1993
- Chairman, European Science Foundation EISMINT (European Ice Sheet Modelling Initiative) Programme,
- Chairman, Specialist Panel for the Columbus/Space Station United Kingdom Utilisation Study 1985/86

d. Recent publications (full reference) relevant to the project; if none relevant to the project give other important publications.

66 research papers published since 1970

Contributor of three chapters to book *Antarctic Science*, ed. D. Walton, Cambridge University Press, 1987.

Doake, C.S.M.,1976. Thermodynamics of the interaction between ice shelves and the sea. *Polar Record*, **18**(112), 37-41.

Doake, C.S.M., W.S.B. Paterson, and M. Gorman. 1976. A further comparison of glacier velocities measured by radio-echo and survey methods. *J. Glaciol.*, **17**(75), 35-38.

Doake, C.S.M, 1977. A possible effect of ice ages on Earth's magnetic field. *Nature*, **267**(5610), 415-417.

Doake, C.S.M, 1978. Climatic change and geomagnetic field reversals: a statistical correlation. *Earth and Planetary Science Letters*, **38**(5), 313-318.

Doake, C.S.M, 1978. Dissipation of tidal energy by Antarctic ice shelves. *Nature*, **275**(5678), 304-305.

Doake, C.S.M. and M. Gorman, 1979. Performance of VHF aerials close to a snow surface. *J. Glaciol.*, **22**(88), 551-553.

Doake, C.S.M., 1980. Tracing particle paths in the Antarctic ice sheet. *J. Glaciol.*, **27**(97), 483-486.

Doake, C.S.M., 1981. Polarization of radio waves in ice sheets. *Geophys. J. R. Astr. Soc.*, **64**(2), 539-558.

Crabtree, R.D. and **C.S.M. Doake**, 1982. Pine Island Glacier and its drainage basin: results from radio echo-sounding. *Ann. Glaciol.*, **3**, 65-70.

Doake, C.S.M., 1982. Polarization of radio waves propagated through George VI Ice Shelf. *BAS Bull.*, **56**, 1-6.

Crabtree, R.D., B.C. Storey, and **C.S.M. Doake**, 1985. The structural evolution of George VI Sound, Antarctic Peninsula. *Tectonophysics*, **114**, 431-442.

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Surname	Forenames	Title
CORR	Hugh, Francis, Joseph	Mr

Does the period of your current post exceed the end date of this proposal? Yes/No. If no give details

Yes

Degrees and posts held, with dates and any other information which would be of interest to the reviewer.

1980-1983: University of Essex. BSC(hons). Computer and Communications Engineering

1983-1986: Research officer University of Essex, Active noise cancellation group.

1986-1998: Glaciologist, Ice and Climate Division, British Antarctic Survey

- Research interests: ice sheet dynamics, design, development and deployment of ice-sounding radars, processing and analysis of time series and geophysical data.
- Six summer seasons in Antarctica engaged airborne and ground-based fieldwork.
- Invited participant in the Norwegian Antarctic Expedition, 1992/93.

d. Recent publications (full reference) relevant to the project; if none relevant to the project give other important publications.

Journals

Vaughan DG, **Corr HFJ,** & Doake, CSM, in press. Distortion of isochronous layers in ice by accumulation-rate variations and non-linear ice rheology. *Nature.*

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Surname	Forenames	Title
MORRIS	Elizabeth, Mary	Professor

Does the period of your current post exceed the end date of this proposal? Yes/No. If no give details

Yes

Degrees and posts held, with dates and any other information which would be of interest to the reviewer.

1968:	Bachelor of Science (Upper Second Class Honours Degree in Physics), University of Bristol
1972:	Doctor of Philosophy (Physics), University of Bristol
1973-75	Senior Research Associate, School of Environmental Sciences, University of East Anglia.
1975 - 86	Principal Scientific Officer at the Institute of Hydrology
1986 to date	Head of Ice and Climate Division of the British Antarctic Survey.
1995 to date	Visiting Professor, University of Reading
1996	Guest Professor, University of Innsbruck
From 1999	Research Activities Coordinator, British Antarctic Survey. Responsible for effective delivery of BAS science programmes.

- Member, Council of the International Glaciological Society, 1995-99
- Chief Scientific Editor, 5th International Symposium on Antarctic Glaciology (VISAG), 1993
- President, ICSI (International Commission on Snow and Ice), 1995-2001
- Mathematical modelling of processes in snow. Parameterization of snow-atmosphere interactions sea level rise. Antarctic field seasons: 1987/88 George VI Ice Shelf, Eklund Islands area; 1990/91 Ronne Ice Shelf; 1992/93 Antarctic Peninsula and Alexander Island; 1994/95 Evans Ice Stream and Carlson Inlet.

d. Recent publications (full reference) relevant to the project; if none relevant to the project give other important publications.

Boulton, G.S., **Morris, E.M.**, Armstrong, A.A. and Thomas, A. 1979. Direct measurements of basal shear stress beneath the Argentiere Glacier, France. *J. Glaciol.* **22**, 3-24.

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Tison, J.-L., **Morris, E.M.**, Souchez, R. and Jouzel, J., 1992. Stratigraphy, stable isotopes and salinity in multi-year sea ice from the rift area, South George VI Ice Shelf. *J. Glaciol.* **37**, 357-367.

Morris, E.M., Vaughan, D.G., 1994. Snow surface temperatures in West Antarctica. *Ant. Sci.* **6**, 529-535.

Morris, E.M., Mulvaney, R., 1995. Recent changes in surface elevation of the Antarctic Peninsula Ice Sheet. *Zeitschrift fur Gletscherkunde and Glazialgeologie* **31**, 7-15.

Morris, E.M., Bader, H.-P. and Weilenmann, P., 1997. Modelling temperature variations in polar snow using DAISY. *J. Glaciol.* **43**, 180-191.

17 Description of the Research Project

Proposer(s) should submit a self-supporting account of their proposed project which is sufficiently detailed to enable referees and DC members to appreciate the nature of the project, and to understand how all the resources being sought relate to the project. It is particularly important to explain the respective roles of staff for whom support is sought, particularly any collaborators, any associated personnel, and the principal investigator. The following points should be addressed:

a. Underlying rationale and scientific and technological issues being addressed, relevance to users and potential scientific, practical and socio-economic benefits.
b. Specific objectives of the project, including their potential relevance to UK and international research work in the field, relevance to the NERC mission and anticipated achievements and including datasets.
c. Methodology and approach
d. Programme and/or plan of research
e. Justification for resources being sought.
f. Management of both project and resources, identifying the training and career development opportunities for personnel working on the project.
g. Long term steward ship of resulting datasets for potential re-use by other scientists.
h. Proposals for wider dissemination of results including those relating to the wider public understanding of science.

This account should be presented on **A4 paper in SINGLE-SPACED TYPESCRIPT (MINIMUM FONT SIZE 12 POINT) WITH MINIMUM 1.5 CM MARGINS ALL ROUND** with adequate sub-headings. Case for support must not exceed **TWELVE sides** including references, tables and diagrams and there must be no more than **EIGHT** sides of text.

References may be presented in a smaller font size provided it is sufficiently clear to ensure good quality reproduction.

CASES FOR SUPPORT FAILING TO COMPLY WITH THESE LIMITS AND CONDITIONS WILL NOT BE CONSIDERED.

17.1 **Summary** of **GIANTS - Basin Balance Assessment and Synthesis** (GIANTS-BBAS)

An idea that has come to pervade environmental science over the past two decades is that changes in the West Antarctic Ice Sheet (WAIS) may, within human time-scales, lead to a rise in global eustatic sea level. While a complete collapse of WAIS leading to a 6-m sea level rise is unlikely in the next few hundred years, even a 5% change in the volume of the West Antarctic Ice Sheet could double present estimates of sea level rise in the coming century. However, while Government and general public call for answers, there exists considerable scientific controversy as to whether such an outcome is likely, feasible or even possible.

This proposal describes an integrated project to be called, GIANTS-BBAS which will investigate two key ice stream catchment basins. We propose to establish their present state of balance, to understand why change is occurring in these basins, and predict their likely evolution including non-linearities that would lead to rapid changes and their future contribution to sea level.

The programme of work is a coordinated plan relying heavily on satellite-acquired data, to improve the present state of knowledge and allow us to formulate an optimal programme of fieldwork. We will conduct two field campaigns; an airborne geophysical campaign to investigate ice dynamics and bed characteristics, and an oversnow traverse to measure spatial and temporal variations in accumulation. The airborne campaign will proceed as a collaborative project with the US Support Office for Aerogeophysical Research (SOAR). In analysing the results we will use advanced GIS techniques to establish the spatial variability of the measured parameters and we will provide a rigorous uncertainty analysis. Finally, we will apply techniques of ice sheet modelling to predict future evolution and contribution to sea level.

The basins targeted in GIANTS-BBAS are those feeding Pine Island Glacier (PIG) and Thwaites glaciers (TG) (Fig 1). These glaciers, transport ice from the interior of the WAIS into the Amundsen Sea, and are thought to be key to the future evolution of WAIS. Our calculations show that ranked in order of integrated basin accumulation, the PIG and TG basins have the second and fifth most important basins in Antarctica . Furthermore, the bed beneath these basins is up to 2500 m below sea level, possibly the deepest in Antarctica, giving this region a great potential for rapid collapse. Recent work indicates that these sites are amongst the most important in Antarctica:

- PIG has been identified as the region most likely to be an early site for dynamical collapse of WAIS (Thomas et al., 1979, Hughes, 1981; Stuiver et al., 1981; Thomas, 1984)
- PIG has an unusually dynamic and variable ice - ocean boundary condition (Kellogg and Kellogg, 1987; Jacob et al., 1996; Jenkins et al., 1997; Hellmer et al., in press)
- Rignot (1998) showed that PIG has a grounding line that is retreating at 2 km yr^{-1}.
- Wingham et al. (1998) showed that the basins feeding TG (and possibly PIG) were the only areas in Antarctica with a spatially coherent change in surface elevation in the period 1992-1996.

The relative distance of these basins from Antarctica's main logistical stations mean that they have been little studied in the past, and future fieldwork demands, a well-planned and highly efficient, approach. We believe that the most effective way to achieve this is a collaborative venture between BAS and the US National Science Foundation (NSF), in which we would concentrate sufficient resources in this area to complete the work in one or at most two field-seasons. We thus plan to pursue these scientific goals in close cooperation with our US collaborators.

17.2 **General Background** - the global context for what is proposed, what has been done before, what related work is going on, why is this work important and what will be the impact.

In 1974 a simple model of the behaviour of the grounding line at the junction between ice sheet and ice shelf was developed by Weertman, which eventually led to the widely adopted view that the West Antarctic Ice Sheet (WAIS), being grounded below sea level and deepening inland, was inherently unstable and might collapse if triggered by a reduction in the restraint exerted by Ross and Filchner-Ronne ice shelves (Thomas et al., 1979). Some authors have even suggested a connection with climate change (Mercer, 1978) although this was never widely accepted in the glaciological community. In the past five years these tenets have been tested and found wanting by several findings

- Theoretical models have shown that WAIS might not be affected by loss of ice shelves. (Hindmarsh, 1993; Bentley, 1997)
- While early General Circulation Models (GCMs) predicted magnified climate warming for Antarctica and meteorological data from the Antarctic Peninsula show warming (King, 1994; Harangozo et al., 1997), there has been no consistent warming trend across the continent, suggesting that the major ice shelves and WAIS are not yet threatened by a warming climate.
- While a warming on the Antarctic Peninsula has caused ice shelves to retreat (Vaughan and Doake, 1996) and the grounded ice sheet to thin (e.g. Smith et al., in press; Morris and Mulvaney, 1995), a considerable warming would be required much further south for similar processes to occur in WAIS.
- It has been shown that the first impact of a small rise in air temperature in the Weddell Sea close to Filchner-Ronne Ice Shelf, would be to reduce sea-ice production and thermohaline circulation beneath the ice shelf. This would reduce basal melting and so thicken this ice shelf. (Nicholls, 1997).

At face value these conclusions might suggest that scientific interest in the WAIS would now be waning, but the reverse is true. Other findings have altered the emphasis of research in WAIS highlighting it as a area of major uncertainty:

- Even without increased storm frequency sea level rise during the 20th Century has caused a significant increase in the frequency of destructive coastal floods (Zhang et al., 1997). Thus even fractional changes in WAIS would have significant social impacts.
- Numerical models have highlighted internal flow instabilities that perhaps lead the ice sheets to wax and wane as an irregular response to a regular climate forcing (MacAyeal, 1992; MacAyeal, 1993; Payne and Dongelmans, 1997).
- Numerical modelling of the Antarctic climate under enhanced greenhouse conditions tends to suggest increases in accumulation which would counteract sea level rise (e.g. Ohmura et al., 1996) and as such the Antarctic Ice Sheet may be the only significant mitigator of sea level rise.
- It appears to be unclear if WAIS has ever achieved equilibrium since the Last Glacial Maximum, or whether the process of readjustment is still continuing (Bindschadler, pers comm.).

The importance of establishing the present and future state of the mass balance of the Antarctic Ice Sheet is clear, only the best way to proceed is still to be decided. Broadly, there have been two techniques used to monitor mass balance of ice sheets - approaches that we can term *Credit / Debit* and *Balance of the Account*. The *Credit / Debit* approach seeks to measure independently the mass of input and mass of output over some area and period, and determine the difference (eg. Allison 1979; McIntyre, 1985; Whillans and Bindschadler, 1988). The *Balance of the Accoun*t approach seeks to make sequential observations of the volume of ice in the ice sheet, either by satellite altimetry (Zwally et al., 1989; Lingle et al., 1994; Wingham et al., 1998) or from surface stations (Hamilton and Whillans, 1997; Morris and Mulvaney, 1995). In future the GRACE satellite may also use changes in the gravitational field over the ice sheet to infer changes in ice sheet mass. To date the *credit/debit* approach has always suffered from large uncertainties and has rarely given an a significantly non-zero answer; while the *balance of account* approach gives little or no indication of the cause of change, and thus little indication of future behaviour. Both the present techniques are thus flawed.

To achieve a reliable basis for prediction we must try to understand the possible causes of change and devise specific tests to indicate the mechanisms through which change is occurring, and so by improving our understanding of the basin we will be able to improve our predictive capacity. We consider that the integrated approach described in this proposal provides a promising route towards this goal.

17.3 Principal Aims of the Research - concise statements about what will be delivered by the project

The principal aims of the project are:

- to establish the present state of balance of two key ice stream basins (PIG and TG)
- to discriminate if any imbalance is due to changes in; precipitation, divide location, ice-flow initiated at the grounding line, or ice-flow initiated within the interior of the basin (similar to the surges seen on many valley glaciers)
- to use these findings and an improved understanding of the drainage basin to interpret its past and predict its future evolution and contribution to sea level rise
- to determine 50-year temperature trends in these basins (no meteorological records are available)
- to determine 30-year variability of surface mass balance in these basins

In the course of the study, several other scientific questions will be addressed at little or no extra cost:

- Are there fossil/incipient ice streams lying dormant within the PIG/TG basin? Or, during glacial periods are there more/less ice streams or do the present ones simply alter in size to accommodate changes in accumulation?
- Why do some deglaciations stop before others? Is the subglacial topography a control on interglacial sea level?
- Is there a tectonic fault between the Marie Byrd and Thurston Island crustal blocks?
- What are the gross rates of isostatic rebound (>±2 cm a^{-1}) in this area?

17.4 Background Specific to the Proposed Project - the specific relationship of this project to others undertaken or to be undertaken in the future, evidence of track record

17.4.1 Relationship to other projects

Section 18 and the attached GIANTS Programme Statement describe how this project sits within a GIANTS programme.

17.4.2 Results of recent work at BAS

In preparation for the proposed project we have begun to collate data from the PIG and TG basins in GIS (Figures 1-6). These data include, oversnow traverse data from the 1950s and 1960s, airborne survey data from BAS and the Scott Polar Research Institute /NSF/Technical University of Denmark programme during 1970s and 1980s, and more recent satellite altimetry. An opportunity was taken during the 1997/98 field season to fly an airborne geophysical sortie from Siple Station (abandoned) to the icefront of PIG. Together these data have allowed us to make new inferences concerning the PIG basin which were presented by Corr at the AGU Chapman Conference on the West Antarctic Ice Sheet (Orono, Maine, Sept, 1998):

- Using a digital elevation model based on ERS-1 satellite altimetry we have accurately delineated the catchment basins for PIG and TG (Fig. 3)
- Integrating accumulation over the basins shows that PIG and TG have, respectively, the second and fifth highest balance fluxes of all Antarctic outlet glaciers or ice streams
- Satellite interferograms of the PIG basin (Stenoien, pers comm.) indicate tributary ice streams 200 to 300 km further inland than the previously identified onset of streaming (Luchitta et al., 1995). Our analysis of satellite altimetry (Bamber, 1994; Fig. 4) indicates a further, larger tributary ice stream.
- Analysis of the new radar data indicates that the margin of this new tributary glacier is marked by a step in the bed elevation, a change in the character of the ice-base reflection and a significant reduction in the driving stress (from 90 to 30 kPa). These conditions persist over 200 km to the grounding line.
- At the grounding line, PIG requires a massive increase in driving stress (to 150 kPa) to overcome a bedrock obstruction. This suggests that a small change in the position of the grounding line would have a substantial influence on the force balance of the glacier (cf. Rignot, 1998).

17.4.3 Track record

The primary members of our team have an excellent track record in all technical areas required:

- *ice dynamics* - Doake & Vaughan have published more than 20 journal papers in 1990s (Section 16)
- *satellite data synthesis* - Doake & Vaughan have published 10 journal papers and maps in 1990s, Doake is/has been PI for, VECTRA, RADARSAT, ERS-1/2, SPOT.
- *system design* - Corr & Doake have designed and built digital, chirped and phase-sensitive ice sounding radars.
- *airborne survey* - Corr, Doake & Vaughan have completed over 10 seasons of airborne fieldwork.
- *ice coring traverses* - Morris has completed 4 seasons of oversnow traverse and has developed the Neutron Density Probe.
- *GPS* - the group has extensive experience of long-baseline, carrier-phase GPS acquisition and processing
- *GPR* - Vaughan, Corr & Doake have experience of GPR acquisition, processing and interpretation
- *ice sheet modelling* - Hindmarsh (BAS-Collaborator) is an expert and has written several seminal works.
- *ice core analysis* - Mulvaney (BAS-Collaborator) is an expert in analysing ice core and managing chemistry labs.
- *PIG and TG area* - Vaughan was invited by the American Geophysical Union to write a review of PIG for a special issue of the Antarctic Research Series devoted to the West Antarctic Ice Sheet.
- One capability we must improve is the routine processing of satellite data - we intend to employ a new recruit with experience of processing satellite altimetry and SAR.

17.5 Research Methodology - how will the research been done, how will collaborators be involved

The GIANTS-BBAS project has several distinct elements which have different life-spans within the project. Time lines for these elements are shown in the following table and then each element is described in detail in sections 17.5.1-17.5.6.

Element		1999		2000		2001		2002		2003		2004	2005
1. Satellite reconnaissance													
2. Fieldwork planning													
3. Airborne geophysical survey													
4. GPS campaign													
5. Oversnow traverse													
6. Chemical analysis													
7. Glaciological Analysis													
8. Predictive modelling													
Density of shading reflects the workload in each period.													

17.5.1 Satellite reconnaissance

GIANTS-BBAS researchers: Satellite data analyst, Doake, Vaughan

Collaborators: US SOAR Group, Wingham (UCL) (letters of support are attached in Annex 1)

Satellite data have improved considerably over the last decade and many of the important parameters for ice sheet research are now available from satellite data

- Surface elevation is available from satellite radar altimetry, and in future from satellite laser altimetry
- Ice sheet stress is available from satellite SAR (Vaughan et al., 1994, Vaughan, 1993)
- Ice sheet velocity from interferometric SAR (Goldstein et al., 1993; Frolich and Doake, 1998) and feature-tracking (Luchitta et al., 1995; Corr et al, 1996)
- Flow tracers and crevasse plumes can be observed on a variety of imagery (Crabtree and Doake, 1982).
- Elevation change of the ice sheet (Zwally et al., 1989; Lingle et al., 1994; Wingham et al., 1998).

In the first stage of our programme these data will allow us to improve our basic understanding of the dynamics of the ice stream basins and plan an optimal programme of fieldwork. We will assemble data from; Landsat, ERS-1/2, RADARSAT SAR, AVHRR; and when available NASA's Geophysical Laser Altimeter Satellite (GLAS) and ESA's ENVISAT, to construct a series of glaciological maps of the area.

The flow of the ice sheet in the basins will be mapped to high precision using interferometric analysis of ERS-1/2 and RADARSAT SAR. While we have experience in constructing interferograms using software written in-house, we require the ability to carry out the initial SAR processing on strips of raw data to improve the quality of the Single-Look-Complex (SLC) image which is the starting point for interferometry ; therefore we have requested shared capital to purchase the *Gamma* software package, now the *de facto* standard. This work will be completed in collaboration with the ESA AO3 project, VECTRA group (Coordinating PI - Wingham; PI - Doake).

17.5.2 Fieldwork planning

GIANTS-BBAS researchers: Corr, Morris, Vaughan

Collaborators: SOAR Group, *GIANTS-DANDY*

Fieldwork planning is a crucial element in the success of the project. The optimal choice of field sites and flight-tracks will be made with specific reference to the findings of the BAS Baseline proposal GIANTS-DANDY (See section 18) and the satellite reconnaissance of the previous section. However, it is already clear that integrated field planning will produce several benefits; ice cores can be drilled at airborne survey track intersections, airborne survey tracks can match the area specific requirements of modelling (finite-element) grids; ice cores and 10-m temperature data will be obtained at stations previously visited during oversnow traverses in the1960s (Shimizu, 1964) allowing estimation of any atmospheric warming in the area (cf. Morris and Vaughan, 1994).

17.5.3 Airborne geophysical survey

GIANTS-BBAS researchers: Vaughan, Corr

Collaborators: US SOAR Group, BAS Independent Project-IMPRES, BAS Baseline Programme-ADGPS

We propose to conduct airborne survey of the basin of PIG and TG basins in collaboration with US colleagues from the Support Office for Aerogeophysical Research (SOAR). We have a firm commitment from the steering committee of SOAR to submit a joint proposal for fieldwork to NSF in Spring, 1999. Our discussions with the NSF Office of Polar Programmes indicate that this proposal will be in-line with NSF Policy on the re-build of Amundsen-Scott South Pole Station. We will request logistic support, fuel and a surface camp to support an airborne field campaign in 2002/3. During this campaign both BAS and SOAR survey aircraft will be deployed from the surface camp near the boundary of PIG and TG Basins. This camp will be positioned at sufficient elevation to avoid the areas that suffer high precipitation rates close to the Amundsen Sea (Vaughan et al., in press-b).

Considerable benefits are to be gained from using two survey aircraft; increased productivity during periods of good weather, lower requirement for ground support (per aircraft), complementary radar systems. In addition, the surface camp would provide a base for lightweight survey parties to complete ground-based traverses (section 17.5.5), and is thought likely to be a target for several "piggy-back" proposals to NSF from researchers in the West Antarctic Ice Sheet Initiative (WAIS).

Although it is conjecture to specify the exact parameters of the airborne survey before the detailed satellite reconnaissance is completed, we will estimate the resources it will require. A grid covering the PIG, TG and intervening basin (Fig. 6), at 20 km track-spacing, with 100-km spaced tie lines, requires around 22 000 km of flight track. We estimate, 50 % overhead for positioning and lost data. A total of 33 000 km of flight track, ie 80 hours of survey flight per aircraft. The survey requirements are to obtain, magnetics, gravity and ice thickness, and internal ice layering. Both the SOAR and BAS Twin Otters have routinely acquired these data simultaneously for several seasons.

Although detailed survey of the fast-moving glacier has not been completed, much of the surface of PIG is believed to have pervasive surface crevassing. Crevassing will limit access for surface fieldwork to that which can be achieved using helicopters operating from a ship - and so would only be attempted under the sister project GIANTS-RISOC. For this reason GIANTS-BBAS would be greatly assisted by progress made within the BAS Independent Research Project-IMPRES. It is hoped that IMPRES ice penetrating SAR mounted on the survey Twin Otter will provide an instrument capable of imaging the bed beneath PIG, providing a basis for the modelling of the glacier. If this instrument is available we would intend to deploy it during the airborne field campaign.

Analysis of the airborne survey data will be a cooperative exercise performed with the SOAR group. Travel funds will be obtained from NSF to support a 3-week collaboration period to be hosted by BAS. During this the data sets will be harmonised and a preliminary interpretation completed, the collaboration period will culminate in an open workshop presenting the data to the scientific community. These will include ice surface and bed topography, magnetic and gravity anomaly maps. These data will be interpreted in terms of tectonic and glacial evolution, investigating whether geology controls the position of fast-flowing ice. In addition, the data will shed light on geological uncertainty as to the existence of a tectonic suture between the Thurston Island and Marie Byrd Land crustal blocks. This will be valuable to the BAS Baseline programme - Antarctica in the Dynamic Global Plate System. Results and interpretation of the airborne survey will be published under joint authorship after which the data will be made available to the collaborators. Data will also be contributed to appropriate databases for bed topography (Vaughan, 1997), magnetics (ADMAP, 1995) and gravity (Bell, pers. comm.)

It is anticipated that the flight tracks planned for the survey will extend several ice thicknesses beyond the ice divides. This full imaging of the pattern of internal reflections around the divides will be of particular interest to those studying the special ice dynamics that occur around ice divides (Raymond, 1983; Raymond et al., 1995; Vaughan et al., in press-a). It is anticipated these data and some coincident profiles collected with GPR see below will reveal any recent and past migration of ice divides (cf., Nereson et al., in press; Vaughan et al., in press-a; Waddington, pers comm.). This data should allow the spatial pattern of divide migration to be determined.

17.5.4 Global Positioning System (GPS) campaign

GIANTS-BBAS researchers: Morris, Vaughan
Collaborators: US SOAR Group, GIANTS-DANDY

Navigation of the airborne survey will be achieved using carrier-phase GPS. Data will be referenced to a base-station at the surface camp. Routine post-processing will allow flight tracks to be determined to around 10 cm relative to this base-station. A second base-station on rock outcrop will allow the base station at the surface camp to be fixed with millimetre precision. A further GPS receiver on a monumented rock station, probably in the Crary Mountains (77°S 118°W) would allow accurate positioning to the base station at the surface camp. We already have a GPS receiver suitable for operating unattended mode for several months. Data from this rock station may allow the determination of the vertical movement of ice at the surface camp, which will be available to ground-truth NASA's Geophysical Laser Altimeter Satellite (GLAS). It is likely that Whillans et al. (Byrd Polar Res. Center), will consider a separate application to NSF to complete a point measurement of local mass balance at the surface camp (cf. Hamilton and Whillans, 1997)

Comparison of the GPS records obtained at the rock station with the wider Antarctic network will allow for determination if there is any gross lithospheric uplift (exceeding ~2 cm a^{-1}) in the area around Crary Mountains.

17.5.5 Oversnow traverse

GIANTS-BBAS researchers: Morris, Chemist
Potential collaborators: BAS baseline programme SAGES, ITASE

The ground-based fieldwork is aimed primarily at mapping spatial and temporal variability of surface mass balance across the basins. It will consist of a network of ice cores, to determine local mass balance and variability. The cores will be linked by Ground Penetrating Radar (GPR) profiles to establish spatial variability. This method has been proven by BAS (Mulvaney) on a 365-km traverse of Dronning Maud Land in 1997/98 and was used by Richardson et al. (1997).

The surface mass balance in the area (Vaughan et al., in press-b) is such that 30-m ice cores will sample 30-60 years of accumulation. A 30-m core can be drilled in 2 days using a lightweight manual PICO ice drill. We anticipate that during the airborne survey a four-person traverse party could collect 10 ice cores, log their temperatures, and collect connected GPR data. Annual layers in the core will be identified using Electrical Conductivity Measurements (ECM) and surface balance calculated from these data. In addition, two cores would be analysed for chemical species (eg. Oxygen isotopes) for the purposes of calibrating the ECM-dating.

The vertical profile of ice density around each borehole will be measured using a Neutron Density Probe which was trialed and shown to perform well against standard measurements in the 1997/98 season (Morris et al., 1998)

Two strategies are available for analysing the core data. a) A portable ECM system could be deployed in the field, allowing the cores to be discarded, with only two cores being returned to UK for calibration. b) All the ice cores could be returned to UK and analysed in the cold room, making the cores available for other analyses and other programmes and collaborations. Option a. keeps the logistical requirement to a minimum but discards a potentially valuable scientific resource; Option b. requires additional air support to collect the cores and additional shipping and storage costs. The present proposal is targeted at option a.

The NSF plans to complete similar traverses in this region as part of the International Trans-Antarctic Scientific Expedition (ITASE) will provide additional data of value to this proposal. In turn, the data collected as part of this proposal will make a contribution to the ITASE programme. The proposer has been involved with the ITASE programme by mapping the distribution of recent surface mass balance in Antarctica (Mayewski and Goodwin, 1997; Vaughan et al., in press-b).

We plan to determine the spatial variability of snow accumulation between the ice cores using a Pulse Ekko 100 GPR system on loan from the NERC Geophysical equipment pool. This system operating at 200 MHZ has been proven to show great detail in internal ice layering to a depth of around 90 m (Vaughan et al., in press-a). These layers can be tracked over wide distances and provide a map of surface accumulation variations.

Site selection for the cores is important as there is the opportunity to revisit sites established during traverses in the1960s (Shimizu, 1964). Re-measurement of 10-m temperatures at these sites will provide the best estimate of temperature change over that period that we are likely to obtain from this region. The methods will follow those developed by Morris and Vaughan (1994). This results will be of great value to the GCM modelling of climate change, including the BAS baseline programme - ACP

17.5.5 Glaciological Analysis

GIANTS-BBAS researchers: All.
Potential collaborators: US SOAR Group, others as appropriate

Thus far glaciologists have yet to establish diagnostic tests for that allow us to determine the reason for change in an ice drainage basin. Our present understanding suggests that a glacial drainage basin has possibly four modes of change:

- Precipitation rate changes affecting the surface mass balance
- Migration of the divides with neighbouring basins
- Dynamic change induced from the grounding line (due to ice/ocean or ice/ice shelf interactions)
- Dynamic change induced from internal or basal instability (surging/basal control)

Components of our planned fieldwork are designed to differentiate between these possibilities

- Our programme of ice coring and GPR traverses will highlight recent trends and variability in surface mass balance
- Internal reflecting horizons will allow us to identify divide migration (Nereson et al., in press; Vaughan et al., in press-a)
- The pattern of surface elevation change in the basins as determined by satellite altimetry, will differentiate either; a draw-down of the surface in the basin due to a grounding-line retreat and ice-stream acceleration; or surge-like behaviour initiated from the basin interior.

17.5.6 Predictive modelling

GIANTS-BBAS researchers: Modeller, Vaughan

Collaborators: GIANTS-DANDY

In a sister project, *GIANTS-DANDY,* colleagues will be developing the modelling tools required to reproduce the evolution of the WAIS though the last glacial cycle. In the final stages of this project these models will be applied to GIANTS-BBAS data, allowing us to determine the history and likely future evolution and estimate the attendant uncertainties.

17.6 Project Schedule - the timetable of events and milestones

Table 1. Shows a timetable of proposed events and milestones for the GIANTS-BBAS project. Table 2. Shows a list of the main deliverables that we would expect to be produced.

17.7 Management issues - frequency of review meetings with collaborators, workshops etc

Collaborative meetings will be required at regular intervals, especially during field-planning and data analysis and funds are requested to support these activities. Perhaps, more important, however, is that regular and frequent contact is maintained by the participants by e-mail and telephone. This will be encouraged from the outset.

Data collected under this project will be considered as the property of NERC and those collaborators directly involved with its collection, however, as each phase in the project is completed data sets will be deposited in BAS Archives, and key data sets made universally available through the NERC Antarctic Environmental Data Centre. We request a total of 3 months of AEDC staff time to service this data. This to be divided approximately, 2 weeks in year 1,2 and 3; 1 month in years 4 and 5. Ice thickness data will also be deposited with the BEDMAP database (Vaughan, 1997).

Publication of results will be primarily in the major journals appropriate to the field (e.g.; Nature, Science, Journal of Geophysical Research, Journal of Glaciology)

17.8 Wider Justification - relationship to government objectives of improving quality of life and wealth creation

Global sea level has risen by around 120 m since the end of the last glacial period around (12 ka BP) (Fairbanks, 1989) and while the present rate of sea level rise is twice the mean rate of the last 6 thousand years, it is 10 times slower than during the 1000-yr periods of rapid Northern Hemisphere deglaciations (12 and 9.5 thousand years ago), showing that ice sheets can be a cause of very rapid sea level rise. In the coming century, the greatest threat of unpredicted sea level rise comes from water held in the WAIS. However, it is also the case that increased precipitation over Antarctica is likely to be the only major mitigator of sea level rise. In order to predict the social and human costs of sea-level rise we must first understand and predict the future evolution of the Antarctic Ice Sheet.

17.9 Fit to the strategic policies of important bodies

In August 1997, the NERC Polar Science and technology board prioritised polar science themes and concluded that understanding the drivers of global change was of the highest priority for NERC science. In June 1997, the NERC Polar Science Expert Group (PSEG 1/98/04) identified a number of key challenges for future UK polar science, among these was; "to improve estimates of the stability of ice sheets".

Antarctic Science into the 21st Century (NERC, 1995) identified the "increased concern over the long-term stability of the marine-based portions of the ice sheet", and suggested objectives of investigating the physical controls on the behaviour and extending work on Rutford Ice Stream to other ice streams.

In *Harnessing our Polar Potential: Strategy for Polar Science 1995-2000* (1995), NERC specifically notes that understanding "the stability of polar ice sheets under present and future climates" will contribute to improved *quality of life* for the UK tax-payer (pg. 6), and that poor predictions of sea level rise, or which polar ice sheet contribute with greatest uncertainty, restrict the ability of government to plan sustainable development (pg. 7).

The PI for this project has been invited to be a lead author for the Third Assessment Report of the Intergovernmental Panel on Climate Change - Working Group II (Arctic and Antarctic). GIANTS-BBAS, itself directly addresses the key objectives required to reduce the greatest uncertainty in predictions of sea level rise, as identified in the most recent report of the IPCC (Warrick et al.,1996, pg 396-397).

Table 1. The timetable of events and milestones for the GIANTS-BBAS Project

Date	Target event & milestones
September, 1998	Chapman Conference on West Antarctic Ice Sheet (Inc. workshop on Pine Bay Glacier's called by DGV and SOAR Group - NSF proposal to be drafted)
November, 1998	Submit invited paper on Pine Island Glacier for AGU Antarctic Research Series
Early, 1999	Collaborative proposal to NSF for logistics support submitted, memoranda of understanding drawn up
April, 1999	Remote sensing reconnaissance
Summer, 1999	Receive NSF decision on funding, decision on field camp location, field season date, field-personnel etc
Summer, 2000	First fieldwork planning meeting
Field seasons 2001/2	Fuel emplacement
Summer 2002	Final fieldwork planning meeting
Summer 2002	Complete remote sensing reconnaissance
Field season 2002/3	Oversnow traverse in PIG TG
Field season 2002/3	Airborne survey in PIG TG
Summer 2003	Collaborative analysis of airborne survey data
Autumn 2003	Workshop for final harmonisation and interpretation of survey data (BAS) followed by presentation of data to community
Autumn 2003	Ice core analysis begins
Summer 2003	GPS GPR data processing
Autumn 2004	Ice core analysis ends
Autumn 2003	Modelling of basin and prediction of future behaviour begins
Spring 2005	Completion of project

Table 2. Likely deliverables with target dates (for papers dates are for submission)

Date	Likely deliverables
Spring, 1999	Review paper on PIG for Antarctic Research Series (Invited)
Spring, 2001	Paper(s) on satellite remote sensing reconnaissance
Summer, 2004	Paper(s) on comparison of current and past 10-m temperatures
Summer, 2004	Paper(s) on airborne survey results
Summer, 2004	Airborne survey data sets - via AEDC
Autumn, 2004	Paper(s) on temporal variability on snow accumulation record over past 50 years
Autumn, 2004	Paper(s) on spatial variability of snow accumulation over PIG TG basin
Winter, 2004	Paper(s) on dynamics of PIG TG basin (including mode and cause of change)
Spring, 2005	Paper(s) on modelling past history of PIG TG basin

Spring, 2005	Paper(s) on modelling future evolution of PIG TG basin
Spring, 2005	Submission of data to AEDC and final report

Figures showing existing data and proposed scope of fieldwork in Pine Island Glacier and Thwaites Glacier catchment basins

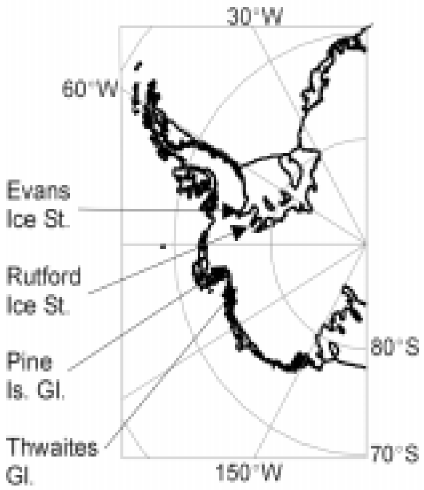

Figure 1.
Location of glaciers and study sites

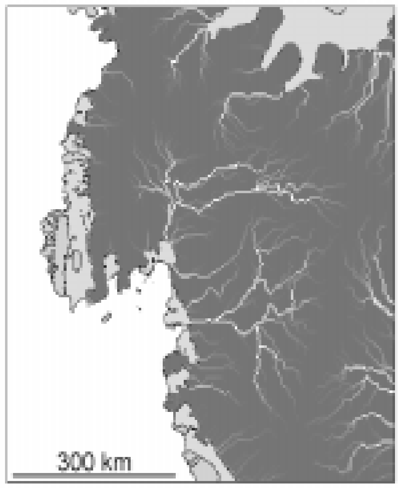

Figure 4.
Concentration of major ice flow derived from ERS-1 topography

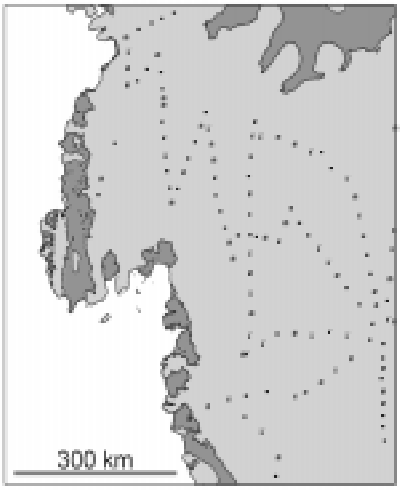

Figure 2.
Traverse data from 1950s and 1960s

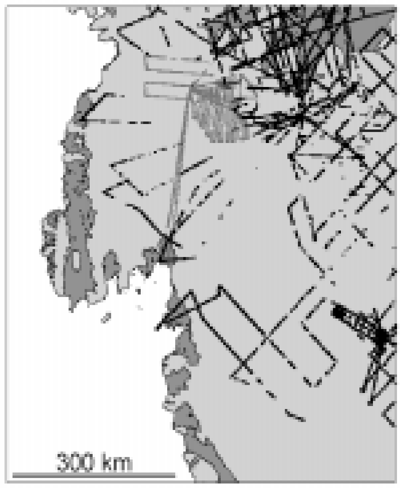

Figure 5.
Airborne survey tracks as of 1998

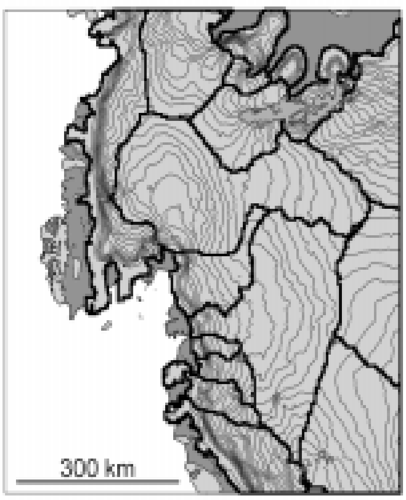

Figure 3.
Rock outcrop, elevation contours, & basin delineation (bold)

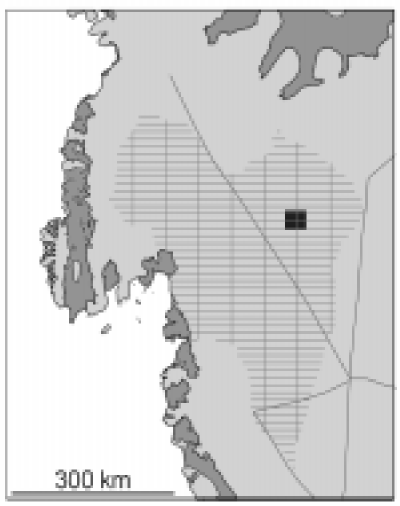

Figure 6.
Density of grids lines achievable in 160 hours of survey flying and proposed ITASE traverses centred on Byrd camp

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18 Summary of the relationship to a BAS Baseline Programme (no greater than two sides of A4)

(If submitted as part of the Baseline Programme process)

The programme of work that the GIANTS group proposes seeks to advance our understanding of ice sheet evolution through a better understanding of its processes and interactions. Over five years, we will seek to make a significant contribution to the question: ***What are the impacts of the Antarctic Ice Sheet on the Earth System?*** It will do this through *projects*, each focussed on an area of science that we see either as an essential precursor to scientific progress across a range of disciplines, as having important socio-economic implications, or that is likely to produce major discoveries in the near future.

The cornerstone of the programme is the project, **GIANTS-DANDY (Data ANd DYnamics: the optimal estimation of the state of the Antarctic Ice Sheet)**. Drawing on the data, and interpretations gained by the other GIANTS projects, GIANTS-DANDY will develop the techniques we require to describe mathematically ice sheet dynamics and evolution. It will critically examine the links between mathematical models and the real ice sheet: our mathematical simplification of physical process to produce an algorithm, and the use of field observations to test or control the model. Such control data will be provided by the project, **GIANTS-LCHAIS (Late Cenozoic History of the Antarctic Ice Sheet)** which will use novel techniques of geological interpretation to reveal snapshots of the ice-sheet configuration during the last 10 M years at two unique sites on the margin of WAIS. Using similarly novel geophysical techniques **GIANTS-TORUS (Targeting the onset region and under-ice systems)** will investigate how the ice sheet interacts with the underlying geology, but will focus on the most critical process in determining the present-day configuration of the ice sheet - namely, how and why does slow moving ice accelerate at particular locations and form rapidly moving bodies of ice? Two field areas will allow comparison of quite disparate ice streams and outlet glaciers. **GIANTS-RISOC (Response of the Ice Shelf-Ocean system to Climate)** seeks to understand the role of the ice-ocean interface, as perhaps the most variable control on the ice sheet, and as a source of globally important water masses. It will compare ice-shelves in cold and warm-water regimes, and model their retreat during the Holocene. This will determine the present-day ice-sheet boundary conditions and those likely to have existed since the Last Glacial Maximum. **GIANTS-BBAS (Basin Balance Assessment and Synthesis)** is the over-arching project in the programme and is there as a case study in which many of the ideas and interpretations gained from the other GIANTS projects will be applied and tested.

By considering the evolution of the Pine Island Glacier and Thwaites Glacier basin we will have the opportunity to focus on an area where many of the specific features on which the GIANTS project focus are present in one important basin - where two massive streaming glaciers which, while rarely visited, have in the last few years been shown to be highly important. In that they rest on some of deepest bedrock in Antarctica, they are only area to be showing a recent change in surface elevation[1], they contain several independent onset regions for ice streaming giving rise to tributary glaciers that coalesce and form the second most active glacier in Antarctica. This glacier drains into an unusually warm ocean, yielding the largest ice shelf basal meltrates measured so far[2], and where the grounding line appears to be retreating[3].

The GIANTS-BBAS project will also have considerable impact on other scientific projects, within BAS, in the UK and in the global arena. Figure 18.1. Shows the major routes for transfer of data and ideas that we anticipate during the programme lifetime.

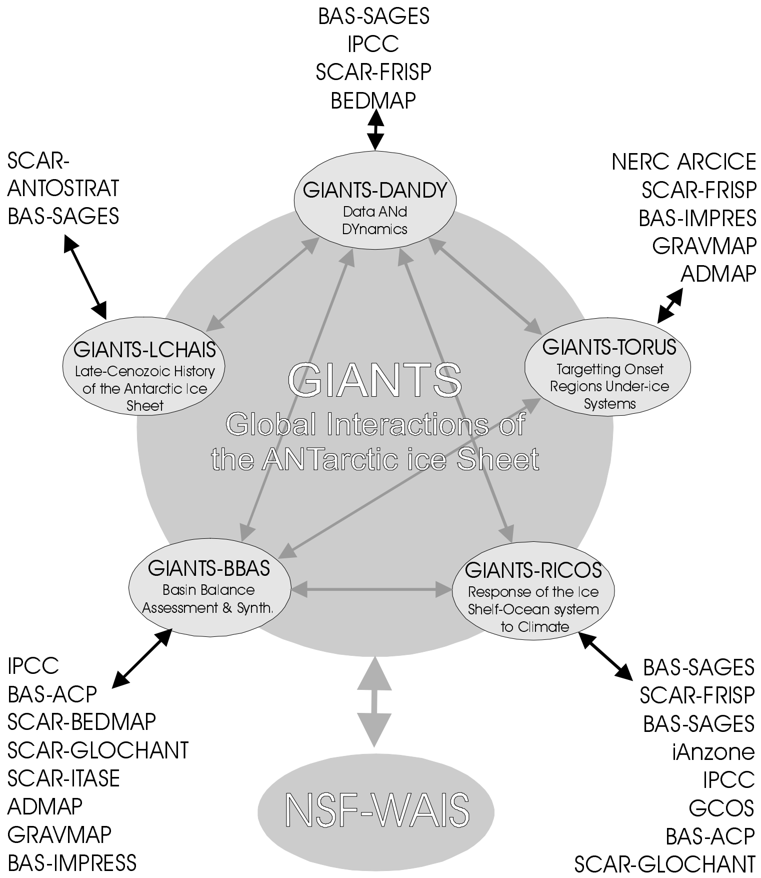

Figure 18.1. Major routes of transfer of data and results between GIANTS projects and other science projects and programmes.

GCOS - Global Climate Observing System
BAS - ACP: BAS baseline project: Antarctic Climate Processes
SCAR-FRISP: Filchner Ronne Ice Shelf Programme
IPCC - Intergovernmental Panel on Climate Change
BAS - SAGES: BAS baseline project: Signals in Antarctica of past Global Changes
iAnzone - Scientific Committee on Ocean Research programme - International Antarctic zone
SCAR -ANTOSTRAT: Antarctic offshore acoustic stratigraphy
BAS-ADGPS: BAS baseline project: Antarctic in the dynamic global plate system
BEDMAP, ADMAP, GRAVMAP: SCAR and community projects compiling geophysical data
BAS-IMPRES: BAS Independent project: Ice Penetrating SAR
NSF-WAIS: US National Science Foundation - West Antarctic Ice Sheet Initiative
NERC-ARCICE: A NERC thematic research programme on Arctic ice masses.

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3-Rignot, E.J., 1998. Fast recession of a West Antarctic glacier. *Science*, , **281**, 549-551.

4-Oppenheimer, M, 1998. Global warming and the stability of the West Antarctic Ice Sheet. *Nature*, **393**, 325-332.

Annex A . Letters of support

Copies of letters of support from the three primary collaborators for GIANTS-BBAS are shown on this page.

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October 1, 1998

Dr. David G. Vaughan
British Antarctic Survey
High Cross
Madingley Road
Cambridge CB3 0ET
UNITED KINGDOM

Dear David,

I am writing in support of your proposal for a geophysical and glaciological assessment of the Thwaites and Pine Island Glacier (TPIG) drainage basins. As we have discussed and were shown at the recent WAIS/FRISP Chapman Conference in Maine, these basins not only dominate the mass output of West Antarctica but there is mounting evidence from satellite observations for non-steady dynamics within these basins.

From the above plan it is clear that the Phase I aerogeophysical program will require the closest US/UK collaboration. Robin Bell and I, in our role as SOAR co-directors, plan to coordinate the US proposal for this component of the work. We believe that the most efficient approach to the aerogeophysical experiments would include jointly designed survey grids (and experimental parameters) combined with shared operations designed to optimize the US heavy- lift capacity for distributing fuel. The ultimate accomplishment would be a suite of US/UK merged data sets (i.e., surface and bed elevations as well as free-air gravity and magnetic maps) made available simultaneously to all TPIG investigators as soon as possible after the field campaign.

It is clear from the enthusiastic response to the planning meetings in Maine that the US glaciology and earth science communities find the proposed efforts in the Thwaites and Pine Island Glacier basins both intriguing and essential to our understanding of West Antarctica's contribution to global change. I believe that the work proposed here represents the best and most cost effective response to this community interest.

Sincerely,

Donald Blankenship
Research Scientist

COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK
LAMONT-DOHERTY EARTH OBSERVATORY

September 29, 1998

David Vaughan
British Antarctic Survey
Madingley Rd.
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Cambridge, CB3 0ET
UK

Dear David,

This letter is to express my strong support for your proposal for joint work in the Pine Island/Thwaites Drainage basin. I feel that this is a key area for understanding the mass balance within the ice sheet as a whole. Support within the US community has been demonstrated by the active workshop participation during the annual WAIS meeting in 1997, and by the attendance at the Pine Island meetings held this month in conjunction with the WAIS Chapman Conference.

This program can only be effectively conducted as an international program with significant contributions from both the US and the British programs. We are being encouraged to develop international programs by the National Science Foundation. In collaboration with Dr. D. Blankenship from the University of Texas and other US collaborators I intend to develop a science plan for addressing the Mass Balance issue you address in your proposal. This science plan will then become the seed for a proposal which we will submit this spring to the U.S. National Science Foundation. We will know the result of that proposal submission in the fall of 1999. There will be additional opportunities to seek funding from the U.S. program prior to the initiation of the program.

The timing of this program also fit well within the present U.S. logistical constraints and long term plans for developing a deep ice coring site in West Antarctica. I look forward to working together on this project.

Sincerely yours,

Robin E. Bell

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Dr. David Vaughan,
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High Cross
Madingley Road
Cambridge CB3 OET

30 September 1998

Dear David,

Basin balance: Assessment and Synthesis

I am very pleased to support your programme in the Pine Island Glacier and Thwaites Glacier drainage basins of the West Antarctic Ice Sheet, and to confirm our interest in collaborating with this programme.

Our experiments show that the Thwaites Glacier basin, uniquely in Antarctica, is falling rapidly at 11 cm/yr. Eric Rignot's work with SAR interferometry has shown that present melt rates of the Pine Island glacier cannot be sustained by its drainage basin. These recent results provide added incentive to properly explore, for the first time, these basins, which, uniquely in West Antarctica, contain ice streams that have no 'buttressing' ice shelves.

We will be working with Eric Rignot and Ian Joughlin of the Jet Propulsion Laboratory to provide the surface velocity of these basins, and to investigate how this varies with time moving inland from the grounding line. Surface observations will be important control data for this activity. More importantly, a much more complete view of the basins will be possible once our velocity data are combined with the ice thickness and other geophysical information which your survey will provide.

I strongly support your proposal, and I look forward to working with you on this most interesting part of the West Antarctic Ice Sheet.

Yours sincerely,

Professor D. J. Wingham, Head of Climate Physics