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Measuring ecosystem response in a rapidly changing environment: the Latitudinal Gradient Project

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Abstract: In the face of climate variability and change, science in Antarctica needs to address increasingly complex questions. Individual small studies are being replaced by multinational and multidisciplinary research programmes. The Latitudinal Gradient Project (LGP) is one such approach that combines a series of smaller studies under a single broad hypothesis to provide information that uses a gradient in latitude as a surrogate for environmental gradients, particularly climate. In this way latitudinal differences can be used to indicate climate change differences. The Key Questions for the LGP were developed via national workshops in Italy, New Zealand, and the USA and via two international workshops at SCAR conferences. Science and logistics are currently jointly shared by New Zealand, Italy and the USA, and cover marine and inland ecosystem studies along the Victoria Land coast from 72º to 78ºS with plans for extensions to 85ºS. The LGP forms part of the SCAR Programme *Evolution and Biodiversity in Antarctica*. This Special Issue summarizes some of the work in the first three years of the LGP (2002–2005), between McMurdo Sound and Cape Hallett, to form a basis for future comparative studies as the research shifts along the latitudinal span in the next decade.

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Introduction

At no time in the past has there been such widespread interest in Earth system dynamics. This interest is fuelled by the current changes to the Earth's climate and our relatively recent increased understanding of whole Earth processes from satellite information and interdisciplinary research projects, such as TOPEX, EOS, World Climate Research Programme (WCRP) and its Climate and Cryosphere (CliC) programme. Some of these changes are due to natural variability, which is caused by a series of overlapping regional cyclical climate system patterns, such as, El Niño Southern Oscillation (ENSO), the North Atlantic Oscillation, the Interdecadal Pacific Oscillation (IPO) and the Southern Annular Mode (SAM) (World Meteorological Organisation 2003, Turner *et al.* 2005, 2006). The linkages between ENSO and the climate of the high latitude South Pacific were noted by Turner (2004). But it is now recognized that on top of this natural variability there is documented climate change driven by anthropogenic factors (Oreskes 2004, World Meteorological Organisation 2003). Analysis of natural climate variations caused by the sun, volcanoes and sulphate particles suggests that variations in these components of the earth's climate system are not enough on their own to explain the recent warming trend. This trend appears therefore to be caused by the emission of greenhouse gases like carbon dioxide (World Meteorological Organisation 2003, Crowley 2000).

The polar regions are particularly sensitive to global scale climate variations. It is widely predicted that large parts of the polar regions will exhibit as much as twice the mean annual temperature change as witnessed elsewhere around the world from climate change mechanisms. Turner *et al.* (2006) have revealed a major warming of the Antarctic winter troposphere, larger than any previously identified regional tropospheric warming on Earth. The Polar Regions are indeed now showing signs of rapid although not consistent change. Recent data show that there has been a complex pattern of change across the Antarctic over the last 50 years, with the Antarctic Peninsula warming more near the surface than anywhere else on Earth (3ºC in the past 50 years) (Turner *et al.* 2005). Since 1950, 86% of glaciers in the Antarctic Peninsula have shown significant signs of retreat (Cook *et al.* 2005). However, other locations on the continent have cooled (Kwok & Comiso 2002). Recent satellite derived data suggests spatial variation in surface melt with some regions of Antarctica having more intensive melting than others (Liu *et al.* 2006). Modelling exercises predict rapid warming in the next 50 years as greenhouse gases in the atmosphere increase and the ozone hole is replenished (Shindell & Schmidt 2004). Impacts of this change are likely to be further compounded by "polar focusing", more pronounced environmental impacts at polar

Table I. (adapted from Vincent 1988). Radiation at the top of the atmosphere as a function of latitude and time of year for the zone 60–90ºS. Data as MJ m^{-2} day^{-1}.

	Month												Total
Latitude	J	F	M	A	M	J	J	A	S	O	N	D	(MJ y^{-1})
60ºS	42	31	19	11	4	2	3	8	18	27	38	44	7417
70ºS	42	28	13	5	1		-	3	13	22	37	45	6174
80ºS	44	26	6	-	-	-	-	-	6	18	38	47	5592
90ºS	44	26	-	-	-	-	-	-	-	18	39	48	5411

latitudes because of the delicate balance of their ecosystems to freezing and thawing.

The questions now being asked of the science community are increasingly complex and revolve around predictions for the future in the face of this change. What will Antarctica be like with (say) an overall 4°C rise in mean annual temperature?

There are several ways to address a question such as this:

1. Small scale models on individual species or habitats based on eco-physiology or small-scale environmental analysis.
2. Larger scale ecosystem models in which temperature and associated climate factors are the drivers.
3. Direct comparisons with a situation at slightly warmer or slightly cooler sites, e.g. with latitude or altitude.
4. Long-term ecosystem studies at a single site.
5. Combinations of these.

There are two parts of the Antarctic continent that lend themselves particularly well to the last point. These are:

Along longitude 60ºW, which includes the Scotia Arc and Antarctic Peninsula and along the Weddell Sea towards the South Pole (Weddell Sea Sector).

Along longitude 170ºE, which includes the Western Ross Sea sector from Cape Adare (72ºS) to the La Gorce Mountains (86ºS).

These two broad transect locations include a coastal strip adjacent to mountain ranges and they both already have long-term environmental monitoring information, they each include a Long Term Ecological Research (LTER) site (www.lternet.edu) (McMurdo Dry Valleys and Palmer Station) and each of these locations have a number of national science stations and ongoing programmes. In 2005, for instance, the Italian "Mario Zucchelli" station at Terra Nova Bay was accepted into the Italian National LTER network, in view of the data recorded in this area over the last 15 years.

The seasonal variability in solar radiation is at its most extreme at latitudes 60–90ºS (Table I, from Vincent 1988). At Cape Adare (72ºS), there will only be two months of the year when less than 1MJ m^{-2} day of radiation reaches the atmosphere, but at the Beardmore Glacier (85ºS) there are 6–7 months of the year with less than 1 MJ m^{-2} day. North–south gradients in enhanced UV radiation effects resulting from spring ozone depletion may also be expected. In these conditions it is likely that species composition will change and species diversity may fall as latitude increases with fewer species adapted to extreme southern conditions. There is evidence to suggest that this solar radiation gradient is followed by gradients in temperature and gradients in ecosystem response, albeit in a complex manner.

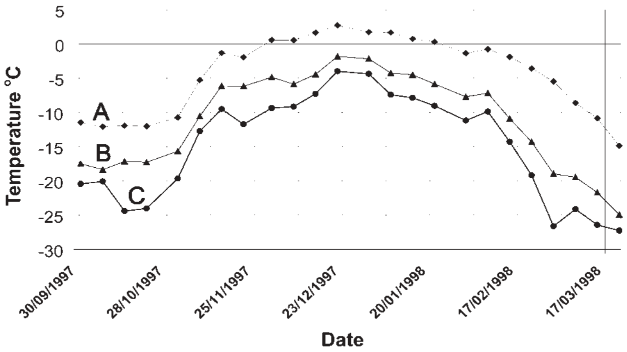

Fig. 1. The average weekly temperature (ºC) for three sites at different latitudes (A = 71.89°S, 171.21°E; B = 74.95°S, 163.75°E; C = 79.95°S, 165.13°E) along the Victoria Land coast are shown for the timeframe of 30 September 1997 to 20 March 1998. Elevations are all low, ranging from 30 to 80 m a.m.s.l. An important feature is the extended period of time above freezing at the lowest latitude site. Note that freeze/thaw cycles are not visible by this averaging. The data are derived from the Automatic Weather Station Project run by Dr Charles R. Stearns at the University of Wisconsin-Madison funded by the US National Science Foundation.

In the Ross Sea sector, significant differences in the non-marine physical environment measurable along latitudes 72–86°S are found in temperature, solar radiation, humidity, glacier movement and the biogeochemistry of meltwaters. In the marine environment differences occur with the dominating influences of light, ocean currents, tides, sea ice and ice shelf coverage, depth and the sea floor substrate. For example, weekly air temperature variations with latitude are shown in Fig. 1 with data from three Automated Weather Station (AWS) datasets for the 1997/98 year.

Ecosystem responses can be seen, for instance, at Cape Hallett (Fig. 2) where extensive areas of terrestrial moss flush (Brabyn *et. al*. 2006), are found. In the McMurdo Dry Valleys (78ºS, Fig. 2) moss flush areas are found occasionally (Schwarz *et al*. 1992), but at 80ºS and higher latitudes no moss flush areas have yet been recorded.

Similarly in the marine littoral zone macro-algae are abundant and luxurious at Cape Hallett and Terra Nova Bay, while further south in McMurdo Sound these organisms appear to be at their limits of survival; (Schwarz *et al*. 2003). Marine algal communities along the Victoria Land

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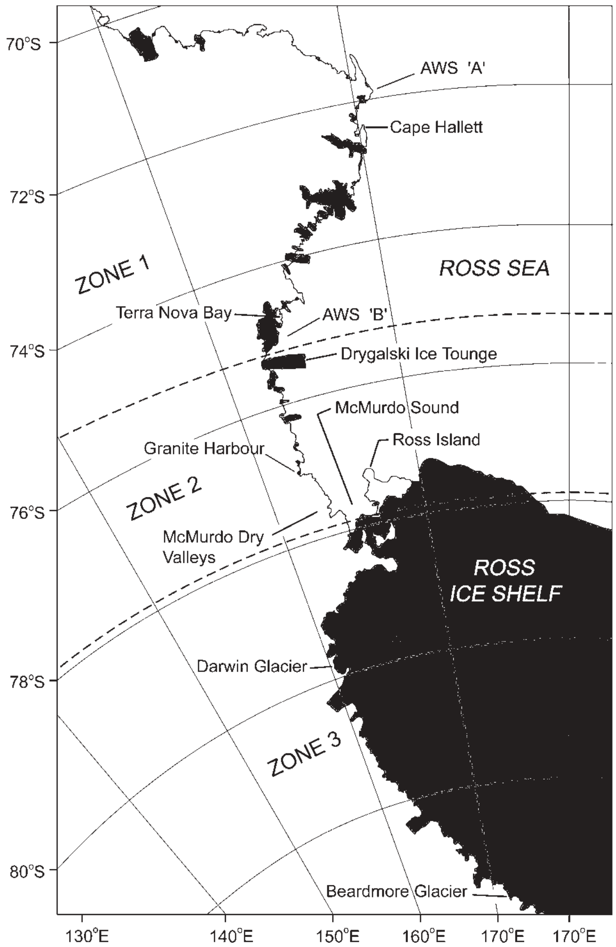

Fig. 2. The Victoria Land Coast from Latitude 72º–84ºS showing sites mentioned in the text, the locations of the Automatic Weather Stations mentioned in the text and the location of the McMurdo Dry Valleys Long Term Ecological Research project.

coast differ significantly in their latitudinal distribution and composition (Smith *et al.* in press). For example, *Himantothallus* and *Desmarestia* are absent south of Cape Hallett, and *Phyllophora* is found in shallower waters towards the south. In McMurdo Sound the abundance of macroalgae is reduced, and their bathymetric range is narrower than elsewhere. This apparent north–south phytogeographical gradient, with algal belts decreasing in importance to the south, is probably due to decreased irradiance (total annual photon fluxes, as well as the number of days of 24 h photoperiods), the longer persistence of the pack ice (which scours the seabed and also reduces total irradiance) and the formation of anchor ice. The latter plays an important disturbance role in McMurdo Sound at depths of 20–25 m where it affects up to 70% of the sea floor (Dayton *et al*. 1970, Battershill 1989, Dayton 1989), while it is nearly absent from Terra Nova Bay. Thus, the shallow water benthos in the two areas can be significantly different (Miller & Pearse 1991).

The concept of a research programme, which uses a gradient in latitude as a surrogate for environmental gradients in Antarctica is not new. For instance Janetschek (1970) first proposed a gradient approach based on latitude, elevation and distance from the coast as a means of analysis of Antarctic fauna. However, in the last decade momentum has increased in pursuing this concept because of the pressing need to address complex questions related to climate change (Berkman *et al*. 2001a, 2001b, 2005). For instance, microarthropods are one of several groups of organisms that are now being studied at different latitudes with a view to using latitudinal differences as an indicator of climate change differences (Sinclair & Stevens 2006).

Developing the concept

We are grateful to our colleague Dr Paul Berkman for his early enthusiasm in promoting discussions on this concept. Dr Berkman began a number of international discussions between Italy, New Zealand and US scientists on the use of a latitudinal gradient approach, which led to a series of national workshops.

1. Italy: *Victoria Land Coastal Programme* – Cattaneo-Vietti *et al*. 2000.
2. New Zealand: *Latitudinal Gradient Project* – Peterson & Howard-Williams 2000.
3. USA: *Latitudinal Ecosystem (LAT-ECO) Responses to Climate across Victoria Land, Antarctica* – Berkman *et al.* 2001a.

These national workshops were followed by an international workshop “Latitudinal Gradients in Victoria Land” at the SCAR Biology Symposium in Amsterdam (Berkman *et al*. 2001b). As a result of these workshops Italy, New Zealand and the USA have undertaken joint studies under the framework of the Latitudinal Gradient Project (LGP). Subsequently, the Latitudinal Gradient Project was linked with the SCAR Programme *Regional Sensitivity to Climate Change* (RiSCC) and is now integrated into SCAR’s new Scientific Research Programme *Evolution and Biodiversity in the Antarctic* (EBA) and specifically into Work Package 4 of EBA: “Patterns and diversity of organisms, ecosystems and habitats in the Antarctic, and controlling processes”. One of the key areas of Work Package 4 is specifically aimed at: “Latitudinal or environmental gradients: how does marine, and terrestrial, and limnetic diversity vary along gradients (Local, Regional, Global)?” It is recognized that important areas to study will be the Antarctic Peninsula and Victoria Land. This recognition, together with other links to EBA were discussed at the Latitudinal Gradient Project Workshop at the SCAR Open Science Conference in Hobart, Tasmania, in July 2006 (see www.lgp.aq).

In the various formative workshops of the LGP, a number of hypotheses and key questions were proposed.

The Amsterdam International Workshop produced the general hypothesis:

> *Ice-driven dynamics control the structure and function of biological systems (marine, terrestrial and freshwater) near the limits of life at high latitudes.*

The participants at this workshop and those at the workshop held at the Byrd Polar Research Centre (Berkman *et al*. 2001a) reached agreement on a number of general strategies for the Latitudinal Gradient Project. These are combined below:

An inter-disciplinary approach to ecosystem research is the key to a better understanding of the ecosystem responses to variation in latitude.

Application of a transect approach (i.e. perpendicular to the coast), at the different latitudinal locations along the coastal zone, in order to separate altitude and depth dependence from latitudinal variation.

Application of remote sensing and long-term monitoring to characterize the physical environment at selected transects in addition to process studies.

Establishment of a comprehensive collection of existing information (database) regarding environmental variation, palaeoenvironmental research and ecosystem understanding.

Interaction with the McMurdo Dry Valleys Long Term Ecological Research programme for annual baseline comparisons and historical environmental information.

Recognition that Victoria Land can be separated into three distinct zones relating to the presence and persistence of ice: the oceanic zone, the fast ice zone, and the ice shelf zone (see Zones 1, 2 and 3 in Fig. 2). Within these zones there may be isopleths, which can be defined by integrating existing data.

Ensure the project is closely related to the SCAR research programmes.

Key questions

From the general hypothesis, eight Key Questions have emerged that now provide the basis for the LGP. These are:

1. What aspects of, and to what extent does, ecosystem structure and function (diversity/complexity) change with latitude, and why?
2. What is the role of persistent, large-scale ice structures in defining community composition along Victoria Land (e.g. Drygalski Ice Tongue)?
3. How do ice dynamics (e.g. movement, melt, accumulation and ablation) influence the relationship between solar radiation and primary producers?
4. How does climate affect the availability and composition of free water and how does this change in space and time?
5. How does climate affect the predictability, persistence and extent of sea ice cover along the latitudinal gradient?
6. How are key marine biological processes (such as respiration, photosynthesis and reproduction) influenced by sea ice conditions?
7. To what extent does soil development (e.g. degree of weathering, carbon content and nutrient accumulation) change with latitude and therefore influence terrestrial ecosystems?
8. To what extent are past conditions along the Victoria Land coast preserved in paleoindicators (e.g. glacial, lacustrine and marine cores, and biological records)?

This issue

This special issue of *Antarctic Science* is the first compilation from a series of studies conducted directly under the Latitudinal Gradient Project framework that were carried out from Cape Hallett to McMurdo Sound between 2002–2005. Simultaneously a significant volume of related work on terrestrial ecosystems in Victoria Land that link to the LGP studies presented in this special edition has been published (Wall *et al.* 2006).

We recognize that the latitudinal gradient approach is complicated by local variability at each latitude due to altitudinal differences on land or water depth gradients in the ocean. Local variability also includes aspect, topography, microclimate (Dana *et al*. 1998), geochemistry (Lyons *et al*. 2002, 2005, Borghini & Bargagli 2004) and legacy (Burkins *et al*. 2000). Individual streams, lakes and ponds have unique characteristics, but there are several over-arching features in which they demonstrate simultaneous responses. For instance glacier melt stream flows vary together from year to year, even in different valleys. Lake ice thicknesses tend to increase with latitude south and there are general patterns in permafrost depth along the Ross Sea sector.

The complexities of local variability are drawn out in several papers in this issue that were co-ordinated under the LGP within significant terrestrial and marine logistic operations (see www.lgp.aq). Inland and some coastal marine studies were carried out from the LGP's Cape Hallett camp and marine studies have also been ship based. Italy organized a multinational and multidisciplinary research voyage, in February 2004 aboard the RV *Italica* involving researchers from Italy, New Zealand, Germany, Spain and the USA. The voyage objectives were to undertake a series of studies that provided a latitudinal context to marine ecological community structure, habitats, environments and consequent biochemical, physiological responses, and to use these changes to predict potential effects of climate change.

The study sites included locations in the areas of Cape Adare, Cape Hallett, Coulman Island, Cape Russell and Terra Nova Bay. One set of results for this volume are reported in the papers by De Domenico *et al*. (2006) and Povero *et al*. (2006) examining water column and benthic coupling. They relate mostly to the LGP Key Questions 1, 2 and 3.

At the same time, Italian researchers were hosted on board the New Zealand vessel RV *Tangaroa* during the "BioRoss" research voyage to carry out quantitative studies of the biodiversity of selected marine communities in the Ross Sea. The goals of this project were to describe, and quantify the biodiversity of the benthic macrofauna and fish communities of the north-western Ross Sea shelf, including the Balleny Islands and adjacent seamounts and to determine the importance of environmental variables influencing marine benthic communities, their composition and structure. The paper by Schiaparelli *et al*. (2006) is one of the publications from that voyage.

Marine research was also carried out using coastal sea ice as a platform at Cape Hallett and McMurdo Sound with papers in this volume by Cummings *et al*. (2006) assessing coastal benthic communities in the McMurdo Sound region, Ryan *et al.* (2006) providing a study of sea ice biota at Cape Hallett to contrast with McMurdo Sound, and Sewell (2006) recording larval forms of marine benthos in the plankton at Cape Hallett, comparing these with Cape Roberts and McMurdo Sound. A further set of comparisons along the Victoria Land coast was made by Guidetti *et al*. (2006) whose paper contrasts benthic shellfish at Terra Nova Bay with McMurdo Sound. These papers relate to Key Questions 1, 3, 5, and 6.

Physical and chemical attributes and processes of the terrestrial and aquatic inland environments that address Key Questions 1, 4, 7 and 8 provide a basis for on-going and future ecosystem studies. In this special issue these include assessments of recent climate variations (Bertler *et al*. 2006), moisture availability (Elliott unpublished), aquatic chemical environments and variability (Wait *et al*. 2006, Healy *et al*. 2006), and the aeolian influence of calcium, chloride and nitrate (Witherow *et al*. 2006). An unusual record of soil and soil hydrological processes at Cape Hallett that will be used as underpinning studies for soils further south is provided by Hofstee *et al*. (2006a, 2006b).

The structure and function of inland ecosystems, and their changes over time are covered by the vegetation studies of Brabyn *et al.* (2006) spanning a 42 year period at Cape Hallett, with latitudinal comparisons in biodiversity and ecosystems reported in the papers by Cannone (2006), Novis & Smissen (2006), and Barrett *et al.* (2006). These address Key Questions 1, 3, 4 and 7.

Future plans

The New Zealand component of the Latitudinal Gradient Project will progress to studies at southerly locations to provide a direct comparison with the Cape Hallett area. The chosen sites are at the Darwin Glacier area (80ºS) and the Beardmore Glacier area (85ºS). Marine research will centre on Terra Nova Bay (76ºS) and Granite Harbour (77ºS). Preliminary data have been collected and a literature review completed that is now available on www.lgp.aq. Research will include Holocene climate variability, glacier and surface ice dynamics, soil ecosystems, vegetation dynamics and aquatic ecosystems (ponds and ice covered lakes such as Lake Wilson).

The McMurdo Dry Valleys-LTER continues into its 14th field season in 2006–2007, with future work currently supported by the US National Science Foundation into 2010–2011. These on-going climatology, glaciological, hydrological, biogeochemical and ecological collections will continue to provide a baseline delineating change along the Victoria Land coast (www.mcmlter.org) with one compilation of results of research studies across a wide range of sites in Victoria Land already published (Wall *et al.* 2006).

To fit with the Italian LTER goals Italian research will concentrate studies on biodiversity of coastal marine communities, mainly in Terra Nova Bay, as well as on the main features of the Ross Sea water masses. Under the Italian Antarctic Programme's PolarDOVE research project, invertebrates with shells and carbonate skeletons will provide potential biogeochemical proxies for the features of coastal water mass features (e.g. temperature). For example, the isotopic composition and trace element content of solitary corals (e.g. *Flabellum* spp.) and bivalves (e.g. *Adamussium colbecki* (Smith)) may serve as tracers for the production and dispersion of high salinity shelf waters (HSSW). Future research, in collaboration with New Zealand will focus on how the structure and dynamics of benthic communities are influenced by changes in benthic and pelagic primary production and ice scour. The genetics of key benthic marine species with different larval strategies will be studied to evaluate patterns of gene flux along the Victoria Land coast. Specimen storage and data archiving and management will be in the collections of the Italian National Antarctic Museum (MNA) (http://www.mna.it/) which is now part of SCAR's Marine Biodiversity Information database, SCAR-MarBIN (http://www.scarmarbin.be/) and will link to the Census of Antarctic Marine Life CAML (http://www.caml.aq/).

The Latitudinal Gradient Project will continue to act as one co-ordinating framework for scientific activities between several nations operating in Victoria Land. It will provide a very active focus for one of the work packages in SCAR's *Evolution and Biodiversity in Antarctica* research programme and this special issue is seen as the first of

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several publications that integrate LGP science activities.

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