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Antarctica and Environmental Change: Closing Remarks [and Discussion]

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Antarctica and environmental change: closing remarks

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The purpose of this contribution is to summarize the papers and discussions, to bring out the highlights, and to focus on outstanding problems and uncertainties.

Sixteen years ago Sir Vivian Fuchs and I organized a similar meeting on research in the Antarctic. Since then there has been an explosion of interest in all branches of environmental science in this region. There have been major advances in theory, and improved technology made possible by the rapid development of electronics has made data collection and analysis easier; but above all the difference between the two meetings is in the development of large-scale numerical modelling as a tool. Also there has been an increasing realization of the value of comparisons between the two polar regions, which is brought out by the contributions to this meeting. The meeting has been distinguished by the quality of the science, the clarity of exposition and excellent visual presentations. It is also striking how much cross-fertilization between disciplines has occurred.

The first two papers by G. Weller and H. Cattle, J. M. Murphy and C. A. Senior, addressed climate change, related to increases in greenhouse gases, as predicted by numerical models. The changes are amplified in polar regions by polar feedbacks. Weller predicted warming by 0.3° C per decade: greater than anything that has happened in the last 10000 years. Models suggest that at twice the present CO_2 levels there will be an increase in Antarctic sea ice thicknesses, especially in the Ross and Weddell Seas; in the Arctic a decrease in sea-ice thickness is predicted. That is a striking asymmetry and the question is: is it real?

Observational data show a warming over Asia and North America, but cooling over Greenland and the North Atlantic region, which is most pronounced in winter. In the Arctic too, borehole measurements through the permafrost, to 100 m depth, show temperature increases of 2–3° C over the last century. Also there is a well-documented recession of ice shelves in the warmest sector of the Antarctic, for example the Wordie Ice Shelf. Strong extra-terrestrial influences may be involved and Weller demonstrated that solar sunspot activity and terrestrial temperatures show a striking correlation.

Potential indicators of change are: sea ice, snow cover, mass balance of the ice sheet and biological productivity. Indications are that sea levels will rise by 2–3 mm per year over a hundred years. Weller drew attention to the SCAR Programme on the Role of Antarctica in Global Change, which is being vigorously promoted. Points arising in the discussion included the importance of determining the rates of change and the possibility of rapid 'flip-flops'. What are the underlying processes producing Arctic–Antarctic asymmetries in climate warming and sea ice thickness in the models; are they real?

Earlier simple models, assuming twice the present levels of CO_2, but ignoring sea ice dynamics, showed the largest warming in polar regions in winter. Cattle stated that more recent coupled atmosphere–ocean models, incorporating deep ocean processes and a slower, more realistic increase in greenhouse gases, indicate little change in the climate around Antarctica, as CO_2 levels double. This is due to the key role of deep ocean mixing in the Southern Ocean (but the models still largely ignore the influence of sea ice). In contrast significant warming is predicted in the Arctic except for the North Atlantic region, which shows a cooling. The current models show a sea ice thickening in the Ross and Weddell Seas and hemispheric asymmetry as in the earlier models. There is still substantial room for improvement in the models and firm conclusions are premature.

J. A. Pyle, G. Carver, J. L. Grenfell, J. A. Kettleborough and D. J. Lary discussed an extremely important change on a much smaller timescale: in stratospheric ozone at altitudes of around 20 km. Since the British Antarctic Survey demonstrated ozone depletion, starting in the 1970s, we have learnt a great deal about the dynamics of physical and chemical processes in this region. Polar Stratospheric Clouds are critical in both polar regions, but more striking over Antarctica, due to the influence of the strong Polar Vortex producing stable, very cold conditions. In the Arctic the picture is more complicated, and unexpectedly the cold ozone-depleted region is eccentrically located well away from the North Pole, over the North Atlantic. Major losses of ozone in mid latitudes have now been demonstrated and they are even more pronounced in the Northern Hemisphere than in the Southern Hemisphere.

As to the possible causes of this, they include: dilution, with a diluted atmosphere moving to lower latitudes; processing, where high latitude ClO concentrations move to mid latitudes before ozone loss occurs; and *in situ* depletion, at high latitudes, stimulated by cold sulphate aerosols. In discussion the significance of volcanic aerosols was discounted.

C. Lorius, J. Jouzel and D. Raynaud showed how ice core data from the past can help to predict future changes in climate and other environmental parameters. This is one of the most exciting and significant

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current programmes in Antarctic research, for documentation of the archive of past environments, contained in the polar, ice is crucial to understanding global change, with immense consequences for Mankind. The temperature change, as derived from the ice cores, is closely correlated with methane and CO_2 changes, but on entering an ice age CO_2 concentrations lag behind. The Vostok core has now been extended a further 600 m in depth, extending the timescale from 160 000 years to a tentative 230 000 years. This is now approaching complete cover of two long-scale climate cycles, in the Milankovitch series, each of about 100 000 years, with shorter periodicities of about 20 000 and 40 000 years. This is an extremely valuable data set. Lorius concluded that greenhouse forcing and ice volume forcing explains 90% of the temperature variations. In discussion it was pointed out that the beginning of ice ages is slow, the end abrupt; the mechanism is not yet known and future work should give priority to addressing the problem.

D. J. Drewry and E. M. Morris were concerned with predictions of variations in ice sheet volume on shorter and longer timescales. Most models make relatively simple assumptions, and are misleading if regional differences in response are ignored. The interior ice sheet, the ice shelves and the Antarctic Peninsula are all very different in this respect. The interior ice comprises 60% of the area and contributes 40% of the snow accumulation; ice sheet margins are 25% of the area and receive 37% of the precipitation; but the Antarctic Peninsula, with 7% of the area, has 23% of the snowfall. The Antarctic Peninsula is particularly complex, with a narrow plateau, complex mountainous topography, steep outlet glaciers, and the calving fronts of fringing ice shelves. Accordingly, there is a rapid reaction time.

Simple models were applied on a 100 year timescale. Accumulation occurs in areas below $-11°$ C and in areas of temperatures higher than this some ablation occurs. For a warming climate the models predict a small net sea level rise, caused by changes in the ice volume of the Antarctic Peninsula.

Discussion next turned to the oceans. C. L. Parkinson demonstrated how remote sensing satellite imagery of the sea-ice distribution shows a large seasonal cycle from a minimum of about 4 million km^2 in summer to a maximum of about 20 km^2 in winter, with a variation of $\pm 10\%$ on the maximum extent and $\pm 18\%$ on the annual means. In summer the area of interannual variability far exceeds the area of consistent ice cover, while in winter the interannual variation is confined to the narrow outer band, and to polynyas, such as the 1970s Weddell polynya, which has not recurred. These are important for heat, mass and momentum changes between ocean and atmosphere, and affect regional circulations. Parkinson confirmed the sea-ice thickness findings and also demonstrated a striking, unexplained regional difference in the length of the sea-ice season in the Antarctic: a decreasing trend in the Weddell and Bellingshausen Seas and increasing in the sector from the Ross Sea to Enderby Land.

D. P. Stevens and P. Killworth described the contribution of the Fine Resolution Antarctic Model (FRAM) to understanding the circulation of the Southern Ocean. The Southern Ocean is particularly important to world climate, as the only ocean connecting three major oceans and therefore moving heat between them. Because it is circumpolar – without longitudinal boundaries – it behaves in a similar way to the atmosphere, but on much longer timescales: thus, a particle travelling eastwards at a typical speed of 10 cm s^{-1} would take six years to circumnavigate the Antarctic.

The water flux in the Antarctic Circumpolar Current is about 130–190 Sverdrups (million cubic metres per second), by far the strongest current in the world. Where is is constricted in certain places, such as the Drake Passage, the flow is very fast. Former ideas about a broad, homogeneous current are now seen to be erroneous. In terms of surface velocity the current is a complicated series of eddies and rivers, and this is probably true of the whole body of this current: the deeper flow is strongly correlated with the flow of the upper layers. Especially noteworthy is the prediction in the FRAM model of a series of discrete eddies from the Agulhas Current, south of Africa, one breaking off every day and drifting to the Atlantic at 4 cm s^{-1}.

Validation is difficult because there are few observed data, but the problem has been approached by studying regional patterns of behaviour which pick up the 'hot spots' like the Agulhas eddies. Killworth concluded that modelling has really extended knowledge of how the circulation works and contributed infinitely more 'data' than sea going oceanographers could collect.

P. F. Barker went back over 30 million years in his contribution on the marine sediment record of past climate and the Southern Ocean circulation. This complements and extends by many millions of years the record of the continental ice cores. First, he considered the role of the ice shelves. At its maximum extent the grounded ice sheet almost everywhere reached the continental shelf edge and scraped the shelf clear of sediments, which were redeposited on the continental slope as thick wedges containing the continuous record of past glaciations. These wedges are best developed off major ice streams, especially at the heads of the Ross and Weddell Seas, Prydz Bay, and off the western margin of the Antarctic Peninsula; in these regions coring yields particularly valuable data.

Secondly, he considered the generation of cold Antarctic Bottom Water (AABW), mainly in the Weddell Sea, which transports sediment, particularly where the current is stronger near the continental margins: sediment grain size is thus a measure of past current strength. The AABW ventilates the world ocean along with North Atlantic Deep Water, but its production – under ice shelves – is greatly reduced in the glacial ocean, where ice shelves are grounded, so that at periods of maximum glaciation the deep basins probably tended towards stagnation, with reduced O_2 levels. Thirdly, the sediments carry a record of sea-ice distribution and primary productivity (through biogenic diatomaceous sediments), and of palaeotemperatures, deduced from studies of benthic and planktonic foraminifera at lower latitudes.

The meeting next turned to more biological themes. K. J. Hall and D. W. H. Walton gave a very clear exposition of rock weathering and soil formation and pointed out that the present retreat of many marginal ice sheets in the Antarctic offers new sites for colonization by microbes, plants and animals. Important factors in the development and diversity of communities are water availability and the period of exposure since glaciation. Changes in relation to climate are greatest in the maritime Antarctic and interactions between snow lie, freeze–thaw cycles, wet–dry cycles, and length of summer are critical in determining the extent and rate of change. Different precipitation régimes affect rock weathering, soil development and structure. Over decades all changes are likely to be slow, localized and easily reversed, and very dependent on soil type. The existing model, which explains the development of the present Antarctic soils since the end of the last ice age, may not be helpful for a wetter régime. For the future their presentation included striking pictures of the effects of plastic cloches, placed on apparently barren, frost-sorted soil, inside which a 2–3° C increase in mean temperature, due to insolation, produced a 1500% increase in ground cover. There will probably be an increase in colonizers associated with warmer climates, consequently leading to increased species diversity. More subtle changes can be expected in the invertebrate communities and in invertebrate ecophysiology.

Thus, polar organisms should be among the first indicators of climate change. T. Callaghan, M. Sonneson and L. Somme took the terrestrial Arctic systems as their starting point and applied some of the findings to the Antarctic. CO_2 is very important in stimulating the growth of plants, but the effect of CO_2 increase is likely to be much greater in the Arctic, where there is a suite of responses of higher plants, such as: increasing photosynthesis, stimulation of the fertilizing effects, changes in the quality of plant growth, delayed senescence and decreased decomposition rates. For terrestrial ecosystems as a whole, however, the picture is not clear; unquantified feedback loops might either cancel opposing effects or act synergistically to increase the rate of change.

But there are only two higher plants in the Antarctic, restricted to the maritime Antarctic and it is the cryptogams that are important; for them water availability is crucial because they are not deep-rooted, and there would be no great increase in moss productivity at higher temperatures unless there was higher precipitation. Invertebrate life cycles are coupled with temperature, through, for example, diapause changes and larval growth rates.

Concerning increased UV-B levels, mosses and lichens may be vulnerable, and although higher plants have characters that protect them, they are also likely to be sensitive. Invertebrates are flexible and probably less affected.

Finally, the Antarctic is isolated and with little species diversity, but there could be an increase in immigrants with warmer climates. However, predictions are confounded by the complexities.

Turning now to the sea, J. Priddle, V. Smetacek and U. Bathmann showed how, according to satellite imagery, the northern polar seas appear to be very rich in phytoplankton, in contrast to the south, where it is patchy and poor. But this is more apparent than real, for remote sensing colour scanning only measures a thin upper layer. The Southern Ocean is anomalous, probably due to high wind-induced turbulence increasing the depth of the mixing layer, and so phytoplankton density appears to be low, compared with Arctic waters, where the phytoplankton is confined to a thinner, more stable layer. In the Southern Ocean higher values of primary production are associated with the ice-edge and ice retreat, especially where dense ice concentrations occur. There, melt-water and reduced wind-shear stabilizes the surface layers, and so there is a shallower mixing layer, as in the Arctic. Where the ice retreats rapidly, there is less chance of such stabilization, but where higher ice densities occur the retreat is slower, the surface layer is more stable and primary productivity correspondingly higher near the surface. Abundant krill tend to be correlated with these stable regions, for they are geared to sea ice and graze on ice algae in winter.

The depth of the mixed layer also influences the extent of the biological pump for carbon, removing CO_2 from the atmosphere. The system that would develop in a global warming scenario is very uncertain, but warming should lead to a larger frequency and output of blooms. Priddle *et al.* believe that the system could cope with large scale warming; although the increased UV-B impact should reduce primary productivity by 10–15%, if sea-ice cover decreases there may be more production overall.

A. Clarke and J. A. Crame moved to the seabed, where a diverse marine invertebrate fauna has existed throughout the Tertiary and probably for much longer. In the last 2.5 million years there were some 50 climate cycles, with which the fauna has had to cope, but currently the Southern Ocean average temperature is very stable within narrow limits. Long-term climate change is normal on Earth; it is the rates of change that are important, not change per se.

The benthic fauna is well adapted, encompassing antifreeze production in fish, low metabolic rates, large winter energy reserves in the larval planktonic phase, and good compensation in physiology. The origin of the modern fauna has involved several factors: especially relict survivals, adjacent deep water, and dispersal from lower latitudes along the Scotia arc. In considering shorter term events important factors have been: ENSO phenomena, sudden events, perturbations and glaciations. Previous glacial extensions may have scraped the benthos off the continental shelf, followed by recolonization, but these catastrophes were probably not total. The dominance of nototheniid fishes shows the adaptive radiation of an ancestral form to fill empty niches; clearly something dramatic happened to the previous fish fauna.

As to the future in a global warming situation, the present fauna is markedly stenothermal, with low dispersal rates and the polar frontal zone constitutes a barrier. However, colonization from the north by warmer water species is a possibility as climate change progresses. Certainly the faunas will change; the uncertainty lies mainly in the rate of change.

Over the last 200 years direct human influences, in the form of commercial fisheries, have become important, causing major perturbations to components of the Southern Ocean marine ecosystems, which may have obscured more fundamental environmentally induced changes. First came fur- and elephant-sealing from the end of the eighteenth century, then whaling from the beginning of this century and – in the last twenty years – fisheries for finfish and krill have developed.

I. Everson introduced the objectives and mechanisms of the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) in managing Antarctic stocks, making the point that, with annual assessment, long-term natural trends will automatically be incorporated in management. He described the methods available, giving two examples, krill standing stocks and changes in their annual production. At present, he suggested, we should confine ourselves to regional estimates, not attempt surveys on a circumpolar scale. He demonstrated that annual catches of krill at South Georgia are correlated with estimates of the standing stock made 6 months earlier: an exciting break-through in research. These krill arrive at South Georgia in pulses which are continually replenished from 'upstream'. The fish stock surveys indicate that year class strengths of some species may reflect fluctuations in krill availability. He concluded that we are unable to monitor change on a Southern Ocean scale; local variations in fish abundance at South Georgia may persist for several months; and local reductions of their staple food may have effects on the stocks of predators.

Finally, J. P. Croxall pointed out that in attempting to study environmental change over long periods the fossil record of birds and mammals is not informative. Only the major recent changes in the populations of top predators in the Southern Ocean are documented and they appear to have been largely human-induced. The nature of, and balance between physical and biological influences differ between locations, regions and the types of predator. Different species respond in many different ways; their population ecology varies and integrates effects of changes in the physical environment (e.g. ice) and the biological environment (e.g. food).

Processes, including potentially important influences of the Southern Oscillation, involving seasonal sea-ice extent and distribution, play a minor role, but it is difficult to demonstrate clear-cut correlations. Attempts have been made to relate some fluctuations to changes in krill abundance and availability, without much success. There are still major uncertainties about causes and effects – the physical processes and the responses of seabird, seal and whale populations – which preclude confident prediction of the effects of global warming.

The fluctuations in sub-Antarctic latitudes are more influenced by human exploitation, so one should turn to higher latitudes and attempt to relate ice extent and food availability, as a way of reducing one major cause of variability. The ecology of the higher predators reflects the interaction of prey availability and environmental change, and the way forward is probably to look more closely into survival and recruitment rates, rather than at numbers per se.

The Antarctic region provides a unique natural laboratory for studies of a wide range of elements of environmental change; the meeting has demonstrated the value of interdisciplinary meetings, with a good cross fertilization of ideas between disciplines and between north and south polar regions. A prime consideration for the prediction of environmental change in the Antarctic, and the future management of its natural resources, is the need to allow for uncertainty, a point which has repeatedly been made. The Antarctic is quite different from any other part of the world; among other things it is the most remote, the coldest, highest, windiest continent. Its only significant export is knowledge and the results of Antarctic research have already markedly influenced research in other regions, most notably by the demonstration of the progressive thinning of the ozone layer over the continent, but also in a number of other fields. However, while the demonstration of changes occurring and predicted within the Antarctic region is valuable in itself, the importance of Antarctic research for global change studies is now coming to be appreciated, and a major new programme for SCAR is concerned with global change. Furthermore, this meeting has clearly shown the interest, diversity and vitality of Antarctic research; it has shown that there is certainly no shortage of challenging and relevant problems to be addressed and I conclude that Antarctic science has an exciting future.

Discussion

G. Weller (*Geophysical Institute, University of Alaska, U.S.A.*). When I prepared my paper I was somewhat hesitant to include any reference to the Arctic, as the Discussion Meeting was about Antarctica. I was therefore quite surprised that many papers presented did include the Arctic, often making comparisons between the two polar regions. This is desireable, on two counts: scientifically, because there are many interesting similarities as well as contrasts between the two polar regions; politically, as the polar community is small and its interests are better represented in the global scientific community if it is seen as one and not as two small, separate groups.

B. Stonehouse (*Scott Polar Research Institute, Cambridge, U.K.*). We have discussed possible consequences of shifts in climate, including changes in glaciers, sea level, ecosystems and plant and animal distributions. We have hoped that some of the data might usefully be incorporated in global models that will help us to predict the effects of climatic change. These parameters are not inherently predictive but are consequential, and so are unlikely to detect shifts in their means or model values until long after we have recognized and recorded the climatic change that is responsible for them.

The global circulation models tell us that changes will appear soonest and most positively in polar regions, suggesting that we should focus attention on monitoring polar climates. Are existing networks of climatic stations in polar regions adequate? Are we investing in other methods of measuring climate (such as remote sensing) that will detect changes as they occur?

G. Weller. The traditional meteorological measurements, for example by using Stevenson screens, are still needed but only to provide 'ground truth' for the increasingly important satellite measurements. We have a good network of Stevenson screens in the populated land areas of the globe, but a very poor one in the polar regions and in the ocean areas. To observe climatic trends globally we have to rely on satellites, calibrated against the existing conventional measurements. A better technique perhaps is to look for climate integrators such as snow and ice extent which are sensitive to climate change and can be easily monitored by satellites.

G. de Q. Robin (*Scott Polar Research Institute, Cambridge, U.K.*). May I stress the value of proxy data on climate change. Examples from glaciology are the ice core studies of Dr Lorius and colleagues. Temperature-depth profiles from ice sheets to depths around 300 m are valuable integrators of temperature data over the past century or more. Dr Parkinson's studies of sea-ice extent are a fine example of relevant climatic data obtained by satellite. Satellite altimetry and imagery provide the most promising direct method of monitoring volume changes of the Antarctic ice sheet and its effect on global sea level.

J. C. Behrendt (*United States Geological Survey, Denver, Colorado, U.S.A.*). Peter Barker discussed the sedimentary record. Would he please expand on the significance relative to future climate change. I refer particularly to the late Cenozoic, i.e. the Pliocene to Holocene.

P. F. Barker (*British Antarctic Survey, Cambridge, U.K.*). Studies of the last glacial cycle in sediments are able to establish the polarity and strength of feedback loops within climate and ocean circulation, that can be incorporated into numerical models.

The sedimentary record also offers the past as an analogue of future climate change, if examined and used with care. The marine sedimentary record of climate change over the last 4 million years (Pliocene to Holocene) shows a general cooling, with a superimposed fluctuation at Milankovich periods (20–100 ka) that has grown fourfold in amplitude over that interval, and has dominated the last 0.8 Ma. Today we are at virtually the warmest part of the glacial–interglacial cycle. The best analogues for global warming, from such a starting location, may be (initially) the very peak of the last interglacial (*ca.* 125 ka) and then, over the longer term, the warming that occurred during retreat from a typical Pliocene glacial maximum, within the interval 4–3 Ma ago. Marine sediments of this age range are within reach of conventional piston corers in some localities, and may be sampled by drilling at other sites where an expanded sedimentary section would provide finer-scale resolution.

D. J. Drewry (*British Antarctic Survey, Cambridge, U.K.*). It is important to recognize that existing glaciological models of the extent of the Antarctic Ice Sheet during major glacial periods remain primitive. There is still uncertainty as to whether the ice sheet extended concurrently to the continental break-of-slope at all places around Antarctic. It is known at present, however, that different ice drainage basins exhibit different dynamic characteristics and react somewhat independently. Furthermore, grounding to the shelf edge requires at least 120 m of sea level lowering, sustained over a period sufficient for a complete grounding line migration. Most of the lowest sea level stands during previous glacials have been of only very short duration and there is uncertainty about the magnitude and synchroneity of complete advances. Thus it is probable that substantial areas of the continental shelf surface remained free of grounded ice and hence provided biological refugia.

D. D. Wynn-Williams (*British Antarctic Survey, Cambridge, U.K.*). I consider that most terrestrial organisms are affected more by micro-climatic conditions than those recorded by conventional meteorology. Meteorological observations made at Signy Station are different from conditions at our primary research site 2 km away and at 150 m altitude. At the site itself, data from the local micrometeorology station differ from the immediate area of soil-colonizing organisms whose micro-environment on soil particles is different again.

It is fundamentally important to know how sensitive indicator species such as soil-colonizing cyanobacteria respond *in situ* to defined climatic changes such as temperature and UV-B. However, our experiments using plastic cloches are process studies. Caution must be applied when scaling up data from such studies to represent a site or an island, let alone a continent or the globe.

D. W. H. Walton (*British Antarctic Survey, Cambridge, U.K.*). The question of appropriate scaling is especially pertinent in considering biological reactions to environmental change. The output of climate models is at present very coarse in terms of individual plant response and rarely contains key features (timing, duration and frequency of key extremes such as frost or drought) which determine plant response. It is thus very difficult to match plant predictions against climate predictions.

M. Basson (*Renewable Resources Assessment Group, Imperial College, London, U.K.*). Dr Everson and Dr Croxall brought out two important points: first that we are

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dealing with a highly variable ecosystem and secondly that the system is dynamic and changing. The classical approach to management is to consider the situation where the system or species under consideration is assumed to be in equilibrium. But it is therefore important to recognize that we are dealing with a dynamic system especially in the context of climatic change. We therefore need to change our approach to management to take this into account.

D. J. Drewry. A wide range of ground-based meteorological parameters are still required from Antarctica, particularly within the interior regions where there are year-round research stations only at South Pole and Vostok. Automatic weather stations and in the future more sophisticated automatic geophysical observatories (AGOs) should provide these and other scientifically useful measurements. There are active plans to develop AGOs in several countries.

P. F. Barker. I am concerned that numerical modelling is getting such a bad press in this discussion. There are two unifying components of global change research: the first is satellite observation, which gives synoptic global cover, and the second is numerical modelling. Where, because of logistic or financial constraints, the possibilities for ground-based observation are comparatively so few, numerical models should help us decide where, when and what kind of data are best collected.

J. C. Behrendt. The oversnow traverse program started during the IGY measured mean annual temperature (10 m depth) at about 30–40 km intervals along thousands of kilometres of traverse. I suggest that repeat measurements at some of these locations may show evidence of possible warming as the original data had an accuracy of about 0.1° C.

G. Weller. One of the largest problems confronting global change research deals with the different time and space scales at which research is conducted in different disciplines. Scaling down the global models and data from satellite observing systems to be of use to the biologists doing plot-size measurements, and likewise scaling up the plot measurements to be of use to the modellers are challenging tasks. Modelling is now moving to meso-scale simulations which have greater use to the field scientists, and satellite measurements have increasingly high resolution. Extrapolation of small-scale measurements to larger landscape units, for example through the use of transect measurements, is approaching the problem from the opposite direction.