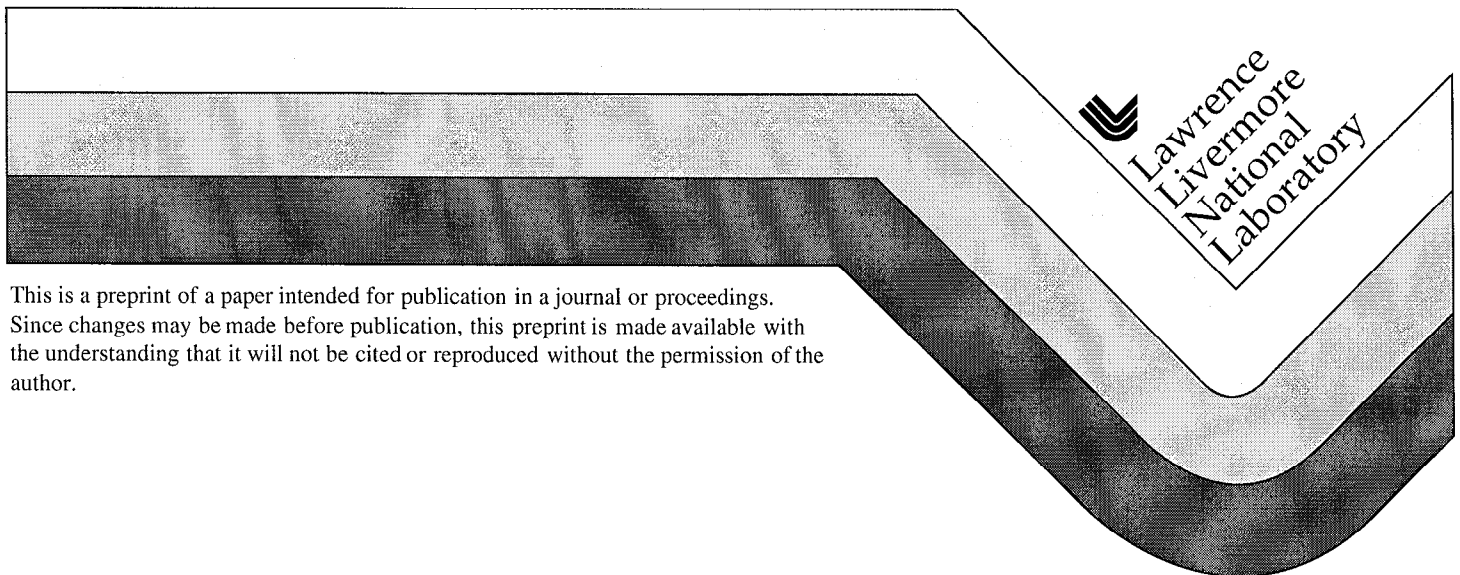


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LONG-RANGE WEATHER PREDICTION AND PREVENTION OF CLIMATE CATASTROPHES: A STATUS REPORT*

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ABSTRACT

As the human population of Earth continues to expand and to demand an ever-higher quality-of-life, requirements for ever-greater knowledge – and then control – of the future of the state of the terrestrial biosphere grow apace. Convenience of living – and, indeed, reliability of life itself – become ever more highly ‘tuned’ to the future physical condition of the biosphere being knowable and not markedly different than the present one.

Two years ago, we reported at a quantitative albeit conceptual level on technical ways-and-means of forestalling large-scale changes in the present climate, employing practical means of modulating insolation and/or the Earth’s mean albedo. Last year, we reported on early work aimed at developing means for creating detailed, high-fidelity, all-Earth weather forecasts of two weeks’ duration, exploiting recent and anticipated advances in extremely high-performance digital computing and in atmosphere-observing Earth satellites bearing high-technology instrumentation.

This year, we report on recent progress in both of these areas of endeavor. Preventing the commencement of large-scale changes in the current climate presently appears to be a considerably more interesting prospect than initially realized, as modest insolation reductions are model-predicted to offset the anticipated impacts of ‘global warming’ surprisingly precisely, in both space and time. Also, continued study has not revealed any fundamental difficulties in any of the means proposed for insolation modulation and, indeed, applicability of some of these techniques to other planets in the inner Solar system seems promising. Implementation of the high-fidelity, long-range weather-forecasting capability presently appears substantially easier with respect to required populations of Earth satellites and atmospheric transponders and data-processing systems, and more complicated with respect to transponder lifetimes in the actual atmosphere; overall, the enterprise seems more technically feasible than originally anticipated.

As might have been expected *a priori*, greater knowledge of natural processes and greater possibility of control over them seem to advance together in this case – as they do in so many others.

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Introduction. Human fecundity is so great that humanity apparently has almost always lived “on the edge,” right up against the limits of the carrying-capacity of the physical environment for the species at the then-current levels of technology, e.g., with respect to habitation, food-acquisition and disease control. Only in the present era and only among modest fractions of the human race – e.g., throughout the First and in much of the Second World – is the population significantly less than the maximum currently possible. Small variations in the physical conditions of the human portion of the biosphere – e.g., rainfall or peak daily surface-air temperature over the next few months – thus continue to be of literally vital significance for the majority of the human race and knowledge of near-term variability of these conditions is of at least considerable significant to everyone. Large-scale and/or large-amplitude variations in biospheric conditions only quite recently observed to occur over the past few hundred millennia surely shaped the human race profoundly – “making us what we are today” – and similarly large variations would be at least profoundly inconvenient and quite possibly massively lethal even today, depending on the time-scales on which they were to re-occur.

These prospects have engaged our attention especially over the past few years, over which interval the seeming fragility of present climatic conditions has become more apparent to every informed observer. At the same time, we note that human capabilities for seeing further, more quantitatively and with greater reliability into the comparatively near future continue to advance exceedingly rapidly during the past few decades, and presently are already so great that it seems feasible to undertake to understand in great detail the future meteorological state of the atmosphere for future-time durations as long as a few weeks. Likewise, the prospect of purposeful human action to forestall climatic catastrophes – *any* relatively abrupt, large-scale changes in climate – seem quite near at hand technologically, and thus to merit serious consideration.

Climate Catastrophes. During the past decade, geophysicists have become extraordinarily adept at retrieving and analyzing more-or-less quantitative indicators of past climate and associated atmospheric conditions, ranging from seabottom cores to those of icepacks of Greenland and Antarctica. At present, the scientific community has laying before it records of global climate and atmospheric composition extending back through four large-scale glaciation cycles occurring during the past half-million years, from the Vostok site in Antarctica and, of even greater present interest, analyses of annual climatic variations over the Northern Hemisphere going back for the past 150 millennia, from the GRIP sites in Greenland. These very extended ice-core-derived time-series are supplemented by other climatic records, notably from seabottom cores, which extend back with reasonably good temporal resolution back for a few dozen millennia, well into the most recent epoch of intense glaciation.

The fundamental picture which emerges from these analyses is one of significant, cyclic time-variability in major climatological parameters – e.g., mean annual temperature – with many stacked periodicities. For instance, in addition to the well-known ~100 millennial cycle of large-scale Northern Hemispheric glaciation, there is evidence for a present-era 1.5 millennium periodicity in Northern Hemispheric temperature of more than 20 cycles’ duration and a few kelvins peak-to-peak amplitude, one whose last minimum was 0.4-0.5 millennia ago. Most disturbingly, during the last interglacial epoch, under prevailing global conditions only slightly – perhaps 1-2 K - warmer than present-day ones, there were several “cold snaps,” intervals of several decades to several centuries duration during which the (Northern Hemispheric) mean temperature decreased 10-15 K over intervals of a few decades, apparently without significant climatological precursors or “warnings” –

at least ones apparent in geophysical records studied through the present. Since mean-temperature conditions duplicating those preceding these earlier 'cold snaps' are currently model-predicted to occur in "business as usual" climate-change scenarios during the coming century, it seems merely prudent to consider ways-and-means of preventing their occurrence – the more so as a minor 'cold snap' in at least the Northern Hemisphere was very recently discovered to have occurred only 8200 years ago and as large-scale circulation in the Labrador Sea is currently predicted by some workers to collapse within the next three decades. While "global warming," if it should occur over-and-above the natural warming to be expected from the 1.5 millennial thermal periodicity just noted, certainly would be far less serious in its human dimensions than would full-scale "cold snaps", it is also natural from a geoengineering perspective to consider technical means of forestalling all-planet warming due to all causes – anthropogenic and natural – should such changes be determined to be contrary to human interests-in-the-large. These form the bases for our present interest in technologies for preventing "climate catastrophes" of both signs and all magnitudes in mean global temperature-change.

We emphasize, as we did two years ago, that we are advocating *only* research in very modest sub-scale into the ways-and-means of preventing climate catastrophes. We remain acutely conscious of the requirements – ethical if not legal, as well – for an unprecedented degree and/or scale of consensus on the part of all mankind before *any* climate catastrophe-prevention steps of full-scale are taken. We believe that the knowledge regarding climate catastrophe prevention which likely can be obtained by a fully transparent and entirely international research program may be effective in informing democratic political processes which alone must determine whether full-scale attempts to prevent catastrophes of climatic origin should be made.

Current Insolation/Albedo Modulation Technological Prospects. Two years ago, we laid before this Seminar what we believed – and still believe – to be the currently-practical technical basis for incrementally shifting either or both of the incoming sunlight to, or the effective mean albedo of, the Earth, so as to change its temperature by amounts of the order of 1 Kelvin. We suggested that controlling the amount of sunlight actually arriving in the lower troposphere – or changing the amount of heat re-radiated by the Earth – seemingly constitute the largest-presently-available levers on the Earth's mean temperature. Placing scatterers of sunlight of any of several distinct types within the mid-tropical portion of the mid-stratosphere appeared to be the most mass-efficient way in which to deploy such insolation-reducing material – with the notable exception of a diaphanous scattering-screen deployed just inward of the Earth-Sun L-1 point, which may be slightly beyond current technological reach. Deploying preferential scatterers of thermal infrared (re-)radiation in similar locations – e.g., what we termed "self-lofting LWIR chaff" – appeared then to be the most overall-effective means of decreasing the effective albedo of the Earth, i.e., of forestalling either a "cold snap" or advent of the next hundred millennia of large-scale glaciation.

Little has changed in these basic respects since our initial presentation. We have continued to examine and to discuss with colleagues these basic approaches, and have identified no significant technical deficiencies with them. We continue to believe that experiments in subscale – involving the deployment of perhaps 1% of a full-scale scattering system, one whose presence could be sensed and studied with sophisticated technical means but which would have completely imperceptible climatic consequences – constitute the method-of-choice in moving out in these research directions. The deployment from ground level of either combustion-generated sub-microscopic alumina particles or of "self-lofting UV/blue chaff" comprised of mass-economized metallic-surfaced balloons of the same basic type – albeit in far greater numbers – which we propose for atmospheric transponders for long-range weather prediction purposes seem to provide the

simplest route to initial results of potential interest. We note in passing that such initial proof-of-concept experiments could be conducted for costs of at most \$10⁸, which are well within private means of several different types.

Insolation Modulation As An Approach To Global Warming. Several schemes have been proposed to counteract the warming influence of increasing atmospheric CO₂ content with intentional manipulation of Earth's radiation balance; ours is merely one of the more recent. Most all such 'geoengineering' schemes involve placing reflectors or scatterers in the stratosphere or in orbit between the Earth and Sun, diminishing the amount of solar radiation incident on the Earth. However, the radiative forcing from increased atmospheric carbon dioxide differs significantly (Figure 1) from that of a change in effective solar luminosity. For example, CO₂ traps heat in both day and night over the entire globe, whereas diminished solar radiation would be experienced exclusively in daytime, and on the annual mean most strongly at the equator, and seasonally in the high-latitude summers (Figure 1). Hence, there is little *a priori* reason to expect that a reduction in the solar luminosity incident on the Earth would effectively cancel CO₂-induced climate change. One might expect, on the basis of the considerations above, that a geoengineered CO₂-laden world would have less of a diurnal cycle, less of a seasonal cycle, and less of an equator-to-pole temperature gradient than would have existed in the absence of human intervention in the climate system. Indeed, such changes, even in the absence of globally and annually averaged warming, might produce damaging regional and seasonal climate change. However, no previous work has addressed this issue of residual regional and seasonal climate change, using a three-dimensional general circulation model.

To investigate these issues, two of us (KC and BG) adopted Version 3 of the Community Climate Model (CCM3) developed at the National Center for Atmospheric Research. This is a spectral model with 42 surface spherical harmonics representing the horizontal structure of prognostic variables: the horizontal resolution is approximately 2.8° in latitude and 2.8° in longitude; the model has 18 levels in the vertical. An important aspect of CCM3 is that it has very little systematic bias in the top-of-atmosphere and surface energy budgets. We adopted a version of the model with a simple slab ocean-thermodynamic sea-ice model, which allows for a simple interactive surface for the ocean and sea-ice components of the climate system. The slab ocean model employs a spatially and temporally prescribed ocean heat flux and mixed layer-depth, which ensures replication of realistic sea surface temperatures and ice distributions for the present climate.

To evaluate the extent to which an effective reduction in insolation might mitigate the climate impacts of increased atmospheric CO₂ content, we performed three model simulations: (i) "Control" or pre-industrial, with a CO₂ content of 280 ppm and a solar "constant" of 1367 W m⁻²; (ii) "Doubled CO₂", with doubled atmospheric CO₂ content (560 ppm), but the same solar "constant" as the Control simulation; and (iii) "Geoengineered", with doubled atmospheric CO₂ content and the solar "constant" reduced by 1.8 %. This reduction in insolation was chosen to approximately offset the radiative forcing from a CO₂ doubling in this model (4.17 W m⁻²), taking into consideration the model's planetary albedo. (In practice, this reduction in solar radiation incident on the Earth could be realized through the positioning of scattering devices between the Earth and the Sun, as noted above.)

Typically, the model needs to run for ~20 years to attain steady-state. For the model

experiments presented here, the model was run for 40 years and the climate statistics presented below are the averaged values over the last 15 years of model simulations. We computed the difference in the mean results for a variety of quantities between the test ("Doubled-CO₂" or "Geoengineered") and Control simulations. Chaotic fluctuations in the simulated climate would introduce some variation between simulations; therefore, we assessed the statistical significance of the difference in the means at each model-grid point using the Student-t test, corrected for the influence of serial correlation.

Comparison of annual and global mean results (Table I) suggests that the reduction in insolation largely compensates for the climatic impacts of increased CO₂ concentrations on surface temperature, precipitation, precipitable water vapor, and sea-ice volume. In the "Doubled-CO₂" simulation, the Earth warms 1.75 K, leading to a reduction in sea-ice volume and an increase in precipitable water vapor. The global mean warming is in the lower end of the 1.5 to 4.5 K range estimated by IPCC. The 1.8% insolation reduction cools the Earth 1.88 K from its doubled-CO₂ state, slightly overcompensating the effect of the CO₂ doubling. We estimate that a scattering of ~1.7 % of solar radiation otherwise incident on the Earth, in this model, would more exactly compensate the effect of a CO₂ doubling. Results from a highly idealized annual-mean general circulation model indicated that the model's annual mean tropospheric response to a 2% change in insolation was of the same magnitude and qualitatively similar to that of a doubling in atmospheric CO₂ content.

Comparison of results for annual mean surface temperature (Figure 2) indicates that geoengineering may largely compensate for impact of increased CO₂ concentrations, despite the differences in the spatial pattern of radiative forcing between changes in CO₂ and changes in insolation. The warming in the Doubled-CO₂ climate is statistically significant (i.e., at the 95% confidence level) over 97.4% of the globe, and is most pronounced in high latitudes where the warming is > 4 K. In general, land areas show more warming than adjacent oceans. In sharp contrast, the Geoengineered simulation shows relatively little surface temperature change. There is a detectable difference (at the 5% significance level) in simulated annual mean temperature between the Geoengineered and Control simulations over only 15.1% of Earth's surface; most of these significant differences are in areas with little change but low variability.

Comparison of surface temperature results by latitude band and season (Table II) indicates that a reduction in effective insolation may largely compensate for the impact of increased atmospheric CO₂, despite the differences in the latitudinal and seasonal pattern of these radiative forcings (Figure 1). The Geoengineered simulation cools most in equatorial regions, because in this region the reduction in radiative forcing from diminished insolation is greater than the increase in radiative forcing from doubled atmospheric CO₂ content.

The Doubled-CO₂ simulation warms more in the winters than summers at high latitudes (Table II), reducing the amplitude of the seasonal cycle. Geoengineering this doubled-CO₂ world might be expected to diminish this amplitude further, because the insolation reduction preferentially reduces solar heating in the high latitude summers (Figure 1), which would tend to preferentially cool. However, poleward of 60°, our Geoengineered case has average winter-time temperatures reduced by 3.82 K relative to the Doubled-CO₂ case, but summer-time temperatures reduced by only 1.83 K, despite the fact that a scattering-type insolation reduction decreases the solar input in summer

more than in the winter. Hence, the amplitude of the seasonal cycle is greater in the Geoengineered case than in the Doubled-CO₂ case (Table II). This occurs because there is more sea ice in our Geoengineered simulation than in our Doubled-CO₂ simulation (Table I). Sea ice tends to insulate the ocean waters from the colder overlying air, reducing the high-latitude wintertime flux of heat from the ocean to the atmosphere. In the Geoengineered case, relative to Doubled-CO₂, the reduction in wintertime ocean-to-atmosphere heat flux results in cooling of the winters and amplification of the high-latitude seasonal cycle, bringing it closer to the Control climate. Geoengineered temperatures in these polar regions, for both summer and winter, differ from the Control case by < 0.08 K.

As might be expected from a reduction in daytime solar heating, the Geoengineered climate has a global mean diurnal cycle over land that is slightly smaller (by 0.1 K) than that of the Control climate. This is a <1% reduction in the amplitude of the diurnal cycle.

Geoengineering the solar radiation incident on the Earth may largely compensate for CO₂-induced changes on the climate of Earth's surface, but it exacerbates the impact of CO₂ on stratospheric temperature (Figure 3). The addition of CO₂ to the atmosphere tends to warm the surface but cool the stratosphere, whereas an insolation reduction tends to cool the atmosphere everywhere. In the Doubled-CO₂ simulation, the equatorial tropopause warms over 3 K whereas the upper stratosphere cools up to ~8 K. The Geoengineering simulation largely compensates for the tropospheric warming but cools the stratosphere by an additional ~0.9 K. Zonal mean temperature changes (Figure 2) are generally significant at the 5% level when the change is >0.5 K. (This calculated cooling of the stratosphere could enhance the formation of polar stratospheric clouds, which could in turn contribute to the destruction of stratospheric ozone. Also, geoengineering approaches involving placing aerosols in the stratosphere could have additional adverse impacts on stratospheric chemistry, as we noted at the outset.)

In general, the model's hydrological cycle (e.g., precipitation) does not show a strong sensitivity to doubling CO₂ (Table I). Changes in the annual mean net fresh water flux – precipitation minus evaporation – were statistically significant at the 5% level over only 13.9% and 3.9% of Earth's surface, for the Doubled-CO₂ and Geoengineered simulations, respectively. As found in other studies, there was significant increase in the net fresh water flux to the surface at high latitudes. Poleward of 60°, the net fresh water flux in our Doubled-CO₂ simulation increases by 0.130 mm day⁻¹, with the change in this flux significant at the 5% level over 51.7% of this area. However, in the Geoengineered simulation, this increase in high-latitude fresh-water flux is only 0.008 mm day⁻¹, and is statistically significant over only 1.8% of this area. It has been suggested that a shutdown of North Atlantic thermohaline circulation could be a consequence of CO₂-induced increases in surface temperature and net-fresh-water flux in the high latitudes. Our results indicate that geoengineering the solar radiation incident on the Earth might diminish the impact of increased CO₂ on both of these quantities, making a shutdown of the North Atlantic's thermohaline circulation less likely. Further, the melting of Greenland and Antarctic ice caps and the consequent sea level rise is less likely to occur in a geoengineered world. Other quantities, including zonal winds and specific humidity, showed little significant change between the Geoengineered and Control simulations.

An analysis of several paleoclimates and paleo-radiative-forcing reconstructions indicated that the latitudinal structure of temperature response to climate forcing is insensitive to the details of the

latitudinal structure of the radiative forcing. In a set of atmospheric GCM simulations with specified ocean heat transport, total poleward heat transport was largely insensitive to the specified ocean heat transport, as changes in atmospheric heat transport largely compensated for changes in ocean heat transport. Our present results and these findings suggest that the response of the climate system to external forcing is somewhat insensitive to the detailed spatial and/or temporal distribution of that forcing. If true, this suggests that geoengineering may be a promising strategy for counteracting climate change, as it may not be necessary to replicate the exact radiative forcing patterns from greenhouse gases to largely negate their effects. Of course, this relative independence of the geographic and seasonal climate response from the details of the climate forcing has its limits: the climate-response "fingerprint" of sulfate aerosols is quite distinguishable from that of carbon dioxide and is unlikely to be compensated for by a uniform insolation reduction.

Our present study considers anthropogenic forcing only from carbon dioxide. Results may differ for other radiatively active gases or aerosols. Simulations using a coupled atmosphere, dynamic sea-ice and ocean general circulation models would include dynamical feedbacks that could amplify the regional or global climate change simulated for geoengineering. Furthermore, we have considered only a steady-state doubled-CO₂ scenario and the transient response of the climate system should also be addressed. To counteract a transient warming, insolation has to diminish over time as atmospheric CO₂ continues to increase; this is seemingly straightforward to arrange with the means which we presently contemplate.

Table I. Annual global mean surface temperature, precipitation, precipitable water vapor, and sea-ice volume for the three simulations described in the text.

Case	Surface temperature (K)	Precipitation (mm / day)	Precipitable water vapor (mm)	Sea ice (10^{12} m^3)
Control	285.50	2.98	24.9	51.8
Doubled CO ₂	287.25	3.07	28.0	38.7
Geoengineered	285.37	2.92	24.2	51.3

Table II. Changes in simulated mean surface temperature (K) in three latitude bands for the Doubled-CO₂ and Geoengineered cases relative to the Control case, for December, January and February (DJF), and June, July and August (JJA).

Latitude Belt	Doubled CO ₂		Geoengineered	
	DJF	JJA	DJF	JJA
90 °N to 20 °N	+2.33	+1.67	+0.15	-0.06
20 °N to 20 °S	+1.31	+1.36	-0.31	-0.27
20 °S to 90 °S	+1.70	+2.01	-0.15	-0.08

Albedo Modulation For ‘Cold Snap’ Prevention. Since it isn’t yet clear what causes a (Northern Hemispheric) ‘cold snap,’ the particular means which would be most effective in terminating-and-reversing the onset of one are likewise somewhat unclear at present. However, it seems intuitively obvious that addition of heat in sufficient quantities would quench such an event, at least in the space- and time-average and likely sufficient to forestall the collapse of Northern Hemispheric food-production. We continue to believe that decreasing the effective albedo of the Earth by increasing the scattering opacity of the stratosphere for LWIR radiation from the Earth’s surface and troposphere is the current means-of-choice for this function. The deployment-from-the-ground of the infrared analog of ‘self-lofting UV/blue chaff’ – small balloons which preferentially transmit incoming sunlight but which reflect LWIR – appears to be the single all-around best approach from the present vantage-point. Balloons composed of very thin metallic – or metalloidal, such as Si – shells fractionally-filled at sea-level with a low-density gas such as H₂ or He seem eminently suitable for this function, and seemingly could be readily generated, in relatively modest quantities for research as well as in full-scale for addressing abrupt, large-scale cooling emergencies. As we noted previously, the total cost of operating such a system is apparently significantly less than \$1 B/year.

Insolation/Albedo Modulation For ‘Terraforming.’ It’s worth a brief note-in-passing that insolation and/or albedo modulation may be the most effective way in which to ‘terraform,’ or render Earth-like for human habitation, several other sites in the Solar system. In particular, Mars seems to be in the grip of a severe ‘cold snap’ of roughly 2.5 Aeons duration, one which would require perhaps a 50 Kelvin temperature increment to relieve. While loading the thin Martian atmosphere with ‘self-lofting LWIR chaff’ to the necessary degree is assuredly the most feasible scheme yet proposed for terraforming Mars, in mass-efficiency as well as in other respects, the deployment of a scattering-screen just Sunward of the Mars-Sol L-1 point is striking in its potential impact; literally one atomic monolayer of material of the area of the Martian disc – optimally deployed, as a scattering-screen – at this location would suffice to scatter sufficient additional sunlight onto Mars to render it Earth-like in mean temperature. This diaphanous scattering-screen thus would be ‘the atomic monolayer(-equivalent) that changed the fate of a planet.’

The potential use of such maximally-optimized means for drastically modulating the surface temperatures of Venus, the large asteroids and – perhaps most interestingly – the Galilean moons of Jupiter is similarly intriguing.

Long-Range Weather Prediction. Lack of reliable and reasonably precise knowledge of the weather two weeks hence is an inconvenience for virtually everyone, but is a still a life-and-death matter for literally hundreds of millions of people – e.g., those who live in flood-prone portions of the Earth’s surface, which tend to be areas of unusually high agricultural productivity and thus of high peasant population density. While not insensitive to the human-suffering dimensions of the present, relatively poor knowledge of future weather, we continue to focus on the economic benefits likely to be realized from improved long-range weather forecasting, simply because the more technically and economically advanced societies – those with significant investment capital readily available – currently seem the most likely to create such advanced weather-forecasting capabilities; we review recent study-results of these benefits and their magnitudes in a little detail. We also review advances which have been made in technical feasibility studies, involving modeling of transponder transport in simulated atmospheres, concerning transponder functional lifetimes, and with respect to realizations of very large-scale computing systems. Finally, we note downward revisions in forecasting system data acquisition scale-estimates, which favorably impact system cost estimates.

Economic Benefits Analysis. Long-range, high-precision and -reliability weather-forecasting could support global economic applications ranging from transportation to agriculture. This section focuses on the potential impact of such forecasting on the various sectors of the U.S. and global economies.

Over the last decade, U.S. government-sponsored National Center for Advanced Technologies workshops have worked to bound the potential of global remote sensing from space. They cover requirements for government, civil, and commercial players and programs; sensors, costs, and revenues, concentrating on the benefits for agriculture, ecology, the environment, land use, and forestry, but giving some guidance on impacts on other sectors.

The U.S. domestic economy is summarized quarterly by the Bureau of Economic Activity, as shown in Table III. It gives the major components of the ~ \$8 T/year of the gross domestic product (GDP). It is divided about 10/30/60% between durable goods, non-durable goods, and services, of which the latter two are most susceptible to weather interruption, divided into about 30 primary sectors, whose weather sensitivity is readily apparent. Since the U.S. GDP currently is about \$8 T/year, the average sector value is about \$200 B/year.

Here we estimate the potential impacts of improved weather forecasts on these sectors at this level of aggregation. Little concrete analysis is available as a guide, so the present process used four steps. The first is to estimate the extent to which improved forecasts could increase the contribution from a given sector. The second is to estimate the time-scale over which the forecast would have to remain accurate to produce that increase. The third is to combine those two parameters to estimate the benefits of improved predictions to each sector. The fourth is to combine these sector estimates into an overall estimate for the whole GDP.

There are uncertainties at each step. The estimates of percentage benefits per sector can at best be plausibility arguments. The estimates of sector time-scales are little more than phase space estimates of the extent to which adverse weather currently impedes activity in those sectors. Their combination with standard logistics curves is plausible, but not unique – and the aggregation of sector benefits into an overall benefit to GDP could omit significant synergies. Once these

approximations are made, we compensate somewhat for uncertainties by studying the sensitivity of its main results to each of these approximations.

The basis for assessment is the extent to which economic activity is impeded by unexpected adverse weather. That groups the economic sectors into three rough classes with major, intermediate, and modest impact. As a percentage of sector activity, the greatest benefits are predicted to be in Aviation, Hotels and Restaurants, Natural Disasters, Construction, Agriculture, and Apparel for fundamental reasons. Environment, Transportation, Trade, Real Estate, and Insurance show lesser benefits. Remaining sectors show indirect effects. Ranking sectors by time-scales puts Natural Disasters, Aviation, Agriculture, Textiles, and Entertainment and Recreation at the shortest; a number of moderately sensitive sectors in the middle; and Construction, Home Furnishing, Environment, Publishing, and Apparel as requiring the forecasts of longest durations.

These contributions to GDP, as percentages of potential benefits and time-scales can be summed over sectors to give the predicted benefits of any given prediction time. The result can be approximated closely by a two-parameter logistic curve. Expected benefits increase linearly to ~\$110, 160, and 180 B/year for forecast validity-times of one, two, and three weeks, which should be attainable. (Four- to six-week forecasts may be possible eventually, but are not essential for our purposes.) The overall benefits of \$100-200 B/year are ~1-2% of the U.S. GDP, which is consistent with a casual inspection of the sensitivity of overall economic activity to weather disruptions.

The values used are for the U.S. GDP, but a long-range weather-forecasting system intrinsically global, both in its requirement to collect data globally and in its ability to disseminate those data and the forecasts derived from them to all nations in near-real time. Thus, any such capability is intrinsically an international system, and its benefits should be estimated accordingly. That can be done only roughly here. The benefit to the U.S. of improved long-range weather forecasts is estimated below to be on the order of \$100 B/year. The U.S. GNP is roughly a third of the combined output of the developed economies; thus, the global impact of long-range weather forecasting could be on the order of \$300 B/year, which would be far more than adequate to justify international development and exploitation of such a capability.

Economic impact. The basis for the assessment of impact is the extent to which economic activity is directly impeded by unexpected adverse weather. This criteria groups the economic sectors into three rough classes characterized by major, intermediate, and modest impacts, whose percentage benefits are shown in Figure 4.

Aviation. The direct cost of fuel and the capital cost of properly positioning aircraft for the successive day's operations are significant costs for commercial aviation. Better measurement of winds aloft would minimize fuel costs and longer-range predictions of weather would permit basing aircraft and crews closer to where they are needed. Avoiding a 60 knot headwind on a cross-country flight could reduce flying time by 10%, and fuel costs even more. Optimally rerouting around even local disturbances could produce savings ~10%. In addition, the atmospheric transponders of the system which we contemplate would provide a direct local measurement of local shear and turbulence, which would provide a comparable benefit in the form of improved safety. Moreover, their responses to interrogation probably could be received and interpreted directly by the aircraft, which might provide valuable local planning information to aircraft in flight. The overall fuel, efficiency, and safety contributions could be expected to sum to roughly 15% operational savings, as shown on Figure 4.

Hotels and Restaurants represent largely discretionary activities, which can be and are often delayed due to adverse weather. That is particularly the case of vacation and resort activities, which are totally dependent on weather. Improved forecasts would improve the consumer's ability to plan outings and the retailer's ability to provide the supplies needed to support them. The two effects are both positive and appear to be of similar magnitudes. As vacations are planned weeks to months

ahead, prediction times on that order could reduce discretionary costs, including secondary impacts on transportation, by tens of percent. A week's prediction could provide similar cost reductions for local restaurants and entertainment. Summing these effects, the total impact could be on the order of the 14% shown. (The slight reduction from the benefit from aviation is intended to indicate that the reductions are less likely to dominate this sector, not to imply 10% precision in the estimates.)

Natural Disasters cost about \$120 B in 1998 and averaged about half that over the past decade. Much of this damage and loss of life could have been avoided, had accurate predictions of the extent of winter storms, the landing points of hurricanes, and the boundary conditions for fires been available. While some loss is unavoidable, the availability of enough time for preparation or evacuation could have avoided much of the loss of property and most of the loss of life. The 13% shown is a conservative figure based on the limited data due to the generally inadequate warning-time available through the present.

Construction is a major sector of the economy. While some components such as office or industrial construction is largely insensitive to weather, other parts such as residential and commercial construction is carried out primarily in good weather. The impact of unforeseen adverse weather on them is three-fold: the direct financial cost to the builder due to the delays, the lost wages to the workers, and the delay of occupancy by the buyer. Each is significant. For example, if a three month project was interrupted for two weeks by unforeseen adverse weather, the builder's construction cost would increase $\sim 2/12$ weeks $\sim 17\%$; the workers would lose $\sim 20\%$ of their wages, and the buyer would have to pay a similar amount for interim facilities. Thus, the total cost of the project would increase $\sim 20\%$. Since major storm fronts take on the order of a week to pass, and do so on the order of each month during the building season, the 12% estimate shown is probably conservative.

Agriculture. Fertilizer, irrigation, harvesting equipment, transportation, and storage are major costs of the food produced, and timing is the essence of getting it to market in a timely and economical way. Improved forecasts could improve each. With longer range forecasts, it would be possible to fertilize where needed and irrigate only when needed. That would minimize the equipment, transportation, and storage needed for interim and final disposal. Two- to four-week predictions of weather and particularly precipitation should make it possible to optimize the combination of input factors and harvest time to maximize production and profits. As the harvest interval at any given latitude is on the order of a few weeks, and adverse weather during harvest can be catastrophic, the potential savings are tens of percent. However, the times that detailed forecasts are needed are a fraction of that total, so the overall benefit is reduced to the $\sim 10\%$ shown, which is in accord with independent estimates.

Apparel purchases are extremely weather-elastic, as indicated by the racks of winter clothing and ski parkas currently marked down 50% or more. While avoiding all of these commercial losses would require 2–3 month predictions, 2–4 week predictions could at least minimize the costs of overproduction, transportation, and advertising. Such predictions would both reduce the producer's cost through more timely purchasing and advertising and the consumer's cost through better informed preparation for the next season or year through sale-shopping. While the benefits in the components above are extremely large, the overall impact is reduced to the 10% shown.

Entertainment and Recreation are, like hotel-usage and vacations, largely discretionary activities, which can be delayed or cancelled due to adverse weather. Thus, improved predictions should make possible improved planning of activities and support, with an indirect impact on transportation and energy requirements. Improved forecasts would improve the consumer's ability to plan outings and the retailer's ability to provide supplies. As entertainment is generally planned a few days to a week in advance, prediction times on that order could reduce costs by tens of percent. The total impact could be on the order of 6–10%.

Environment. Measuring the environment and assuring compliance with environmental regulations is a significant cost today; it will increase substantially to ~\$1 B/year or more under proposed regulations. If anthropogenic global warming is determined to be a real effect, it is likely to increase even further. And for such measurements to be useful and credible, they must be objective and global, which is a unique and powerful advantage of our proposed system. Calibrated, objective measurements of meteorological variables could both support pollutant dispersal calculations and measure their accuracy. Such measurements could magnify the impact of any other measurements. Indeed, they could be essential to gaining broad support for them. Thus, the 6% benefit indicated is a conservative estimate of the benefit of these measurements for any level of environmental measurements.

Transportation is significant for both commercial and recreational purposes and for car, rail, sea, and air carriers, as discussed above. Commuters primarily rely on cars. During some day- to week-long intervals in the winter, car transportation is not feasible in much of the country, so work is delayed and wages are lost. With adequate day-to-week forecasts, some of those transportation losses could be eliminated and a fraction of those lost work-days converted into productive time using the Internet-based home-office technologies that are now developing rapidly. Similarly, during the harvest season, it is now necessary to pre-position railroad cars in anticipation of good weather and early harvests. Improved forecasts could improve pre-positioning and maximize the reuse of rolling stock. Sea transport would benefit from fuel savings from more efficient route planning with 1–2 week forecasts, which could lead to a direct fuel, crew, and capital savings of ~ 5%, leading to the composite estimate shown.

Trade has two dimensions, domestic and international. The ability to use forecasts to eliminate overproduction and target advertising to times of consumer availability is discussed above. Consumers shop during good weather; shopping is reduced during periods of rain or snow. Improved forecasts would permit consumers to plan their shopping and allow retailers to optimally schedule re-supply. That is true both domestically and internationally. With 2–4 week forecasts, global shopping and re-supply requirements could be met more efficiently and shifted off periods of slack demand, which could result in savings of several percent.

Real Estate. As noted above, commercial and private real estate is primarily constructed during periods of good weather, particularly the latter. Thus, the cost to each is directly proportional to the fraction of unanticipated adverse weather. Some of those costs—particularly the dominant labor costs—could be largely eliminated with 2–4 week forecasts, which would make it possible to shift workers to other regions with more acceptable weather. A second dimension of real estate is sales. It is difficult to sell a house in a severe snow storm; it is unpleasant to buy one in an extended rainy warm front. Longer forecasts would make it possible for sellers, buyers, and realtors to schedule their activities and travel to take better advantage of the best weather for each activity, which is assumed to lead to the benefit shown.

Intermediate impact sectors may have significant sensitivity to weather, but it is less easily or fully documented.

Insurance is a major industry in the U.S. and globally. Virtually all cargoes, carriers, crews, repositories, and deliveries are fully insured. Thus, life, property, and casualty rates and volume are all driven by weather-related incidents. Better forecasts could improve trip and transport planning, which could reduce accidents, losses, and rates. Air and maritime travel are important examples. Maritime voyages typically last several weeks; thus, improved forecasts could both permit improved route planning and minimize the probability of catastrophic loss in storms. This improvement would be reflected throughout the investment sector that derives from this insurance underwriting activity. If a typical transport takes a week, and weather delays could cause a delay of

a day, that would cause a loss of ~ 10%. Such delays occur about 10% of the time. Together with catastrophic losses of ~ 1%, that gives the ~3% indicated.

Building Materials production is sensitive to ground conditions at the material source, which under adverse conditions may be impassable; thus, it is highly weather-dependent. With adequate forecasts, it should be possible to schedule production from sites with poor weather and shift workers to sites with adequate weather. That is not practical with current predictions, but multi-week notice should make it possible to optimize site and delay workers to largely eliminate weather delays. As those delays currently occur for a week out of a few months, those benefits could be on the order of ~ 5–10%. Thus, the 2% shown is conservative.

Energy demand varies inversely with temperature on a daily, weekly, monthly, and seasonal basis. Improved forecasts would permit more efficient wheeling and peaking for daily loads, sharing arrangements for weekly distribution, and storage for monthly and seasonal anomalies. The ability to wheel and peak efficiently directly impacts capital costs, which are the dominant elements of the price of power. Sharing arrangements drive transmission investment. And orderly storage could stabilize the swings in prices due to arbitrage that make orderly planning for unexpected phenomena, such as an unexpected January freeze over the U.S., difficult to perform. Better forecasts for conventional sources would also directly impact the demand for and development of alternate sources of energy, as well as that for environmental controls and pollution abatement. The impacts vary widely. Replacing peak capacity with transmission from unaffected regions would reduce costs directly. Capital costs are ~30% of the total; thus, transmission for 3 days of each month could save ~ 10%. Fuel oil is stored at a carrying charge of ~10%, so eliminating disruptions such as the two-month glut experienced in the U.S. in the fall of 1998 would save ~20%. The 2% shown assumes that recent adverse weather patterns are anomalous.

Food Processing (in agriculture and ranching) is strongly inhibited by adverse weather—the former because crops are inaccessible or ruined; the latter because livestock are killed or immobilized. Improved predictions should permit more efficient scheduling of crop maturation and harvesting. It should also reduce costs for transportation, processing, and storage facilities, which are a significant fraction of the cost of the finished product. Better forecasts could also eliminate supply bottlenecks and permit more efficient planning. In agriculture, the direct benefit of saving crops that would be destroyed by adverse weather is discussed above. But the costs of transportation, processing, and storage are comparable. Reducing peak capacity by scheduling separate areas could be done with predictions of 1–2 weeks, the time for trans-shipment. The same could be done with livestock with the 2–3 week warning needed for transport, feeding, and processing. Since the duration of peak activity in each are measured in weeks to months, 1–3 week predictions could save 20–30% of the losses. If such losses were experienced by ~20% of separate geographic areas on the average, this would lead to ~4–5% benefits, which are understated by the 2% shown.

Mining is impacted by the accessibility of open pit sites, which are an increasing fraction of both energy and mineral extraction. With 3–7 day predictions, effort and crews could profitably be shifted to accessible sites, which would save about ~10%. Assuming that would impact ~20% of the sites leads to the 2% estimate shown.

Paper and Forest products production is directly impacted by the accessibility of the forests involved. While that would not be impacted by better forecasts, men and material could be better reallocated to alternative sites or tasks, with several-day to few-week forecasts. The saving is directly proportional to the fraction of days otherwise be impacted, which would lead to savings of several percent. That is also the basis for oil field services for largely the same factors.

Telecommunications services would be improved by better predictions of weather outages, particularly high-volume, high-margin wireless communication, which is increasing rapidly, as

unexpected outages drive requirements for both parallel entry points and their capacity. These entry points are ~10% of the cost of such systems, so eliminating the need for duplication could save on the order of 5% in capital and a like amount in operating expenses.

As a by-product, the availability of global weather measurements could also generate private, commercial, and governmental demand for the rapid distribution of the datastreams so generated. This could further increase the demand for telecommunications services—particularly in that the data taken over a given nation could be immediately processed locally for its benefit as well as fused with global data. Such data would improve global weather awareness, which could create a new economic dimension to the industry.

Modest impact sectors are largely those with centralized, indoor production facilities.

Auto & truck manufacturing & parts are generally at a few centralized sites. It is difficult to distribute the assembly, so it would be difficult to effectively shift work and people even with significant prediction time. However, the workers do have to reach their work-sites, which are largely in northern regions; thus, weather predictions of even days to a few weeks could avoid accidents and losses and enable workers to schedule travel, leading to the 1% estimate shown.

Industrial services are tied to the industries they service, so it is difficult to distribute them. However, workers and products have to reach those sites, so days to weeks weather predictions could avoid accidents and losses to the 1% estimate shown.

Petroleum production is increasingly tied to large rigs in remote areas with adverse weather much of the time. However, crews do have to be rotated safely and products must be removed efficiently. Both operations are strongly weather-sensitive, with delays of days compromising the operation. Thus, day to week forecasts could save ~10% on operations that are ~10% of the entire enterprise, which leads to the ~1% estimate shown.

Textiles are dependent on the harvest and transport of the raw materials. Thus, like agriculture generally, they are susceptible to both crop destruction and delays due to adverse weather. The harvest cycles are again days to weeks, to which the capital-intensive transport system is also sized. Thus, predictions of a week could save crops and production over regions constituting ~10% of the total, leading to the savings shown.

Banking and Finance savings result from more efficient underwriting of industrial and transportation activities, which is complementary to the insurance activities discussed above. If crops, production, and transport are more orderly and less risky, their financing can be more orderly and less expensive as well. If the disruptions are reduced 10% for the riskiest ~10% of the portfolio, that would produce the ~1% benefit shown.

Chemicals are largely produced in large, centralized facilities. However, workers do have to reach them safely, and products must be exported efficiently—both of which are weather sensitive—so day to week forecasts could save ~10% on operations that are ~10% of the enterprise, which leads to the ~1% estimate.

Electrical & electronic products are largely produced in large, centralized facilities, but workers have to reach them safely, and products must be shipped efficiently, which leads to an estimate of a ~1% benefit.

Health care is provided in centralized facilities, but workers, patients, and injured persons have to reach them safely, which leads to a ~1% estimate. A special issue is health care for remote areas, which could be scheduled much more efficiently with 1–2 week predictions.

Home furnishings & appliances are largely produced in centralized facilities, but workers must reach them safely, and products must be shipped, which leads to an estimate of a ~1% benefit. Moreover, home furnishings and appliances are closely tied to home purchases and construction, which are strongly weather-dependent. Thus, improved forecasts, which could regularize home purchases and construction, would also make it possible to schedule home furnishing and appliance

production more optimally, although that is an indirect interaction which is more difficult to quantify.

Investment activity is the basis of capital construction, production, transport, and much of consumption. As each of those activities is weather-sensitive, so is investment activity. Although the direct impact on the volume of investment needed to support those activities is significant, the indirect effect of leveling out those flows could be as significant. Making use of the capital that undergirds these interactions more efficiently by 1% would reduce the cost of financing them by the like amount shown.

Machinery and fabrication are largely in large, centralized facilities, but workers have to reach them safely, and products must be shipped efficiently, which leads to an estimate of a ~1% benefit. Better estimates could also be used to level demand and production schedules.

Miscellaneous services is composed of a large number of sectors that are all sensitive to the need for workers to reach them safely and for their products to be shipped efficiently, leading to an overall estimate of a ~1% benefit.

Cumulative sector impact. Figure 5 shows the cumulative benefits as a function of economic sector in order of decreasing benefits. Cumulative benefits start at about \$60 B/year from Trade, increase rapidly through Construction and Real Estate, then more slow to \$160 B/year by Natural Disasters and \$200 B/year by Environment. Subsequent differential sector contributions are smaller, leading to an asymptotic cumulative benefit of about \$230 B/year, although not all of it could be realized.

Trade gives a differential and cumulative benefit of about \$60 B/year, which is about 1.1% of GDP, primarily because of its large contribution to GDP—its fractional impact from Figure 4 is only about 5%. The ~\$30 B/year contribution from Construction is the product of a smaller contribution to GDP and a larger percent benefit. Real estate gives a contributions of ~\$30 B/year from a larger contribution to GDP and a smaller percentage. Agriculture and Natural Disasters have moderate contributions to GDP and significant percent benefits. Aviation has a modest contribution and a high percentage; transportation a high contribution and modest percentage; hotels and restaurants a modest percentage and high percentage. Other sectors have decreasing percentages, except for Apparel, which has a 10% potential benefit, but only a \$32 B/year contribution to GDP. Thus, these sectors typically have differential impacts < 0.1% of GDP.

About \$150/230 B/year, or ~ 65% of the potential benefit, comes from the first 4-5 sectors: Trade, Construction, Real Estate, Aviation, and Natural Disasters. 87% comes from the first 10 sectors through Environment. The combined contributions from the other 20 sectors is only ~ 10%. These percentages are, however, altered somewhat when their time-scales are taken into account, as some sectors such as Real Estate and Trade have 4-5 day scales, which are difficult to satisfy fully.

Characteristic time scale. The previous section gave some indication of the prediction time scales necessary to realize the benefits estimated there, where prediction time is the duration of accurate forecast required to realize about 50% of the maximum benefit possible from a given sector. Figure 6 summarizes those estimates for each sector. Natural disasters, aviation, agriculture, and textiles have the shortest characteristic times—ranging from 3 to 5 days—in accord with the transient characteristics of storms, wind, rain, and growth that govern them.

The next group—entertainment, health care, and food processing—are also strongly sensitive to weather, but indirectly through consumer choices, timing, and resource scheduling. The group consisting of transportation through energy are sensitive to the direct impact of adverse weather on workers, transportation, and trans-shipment—as are telecommunications, services, electrical, auto, and machinery—on slightly longer time-scales. Insurance, finance, and investment are sensitive on the 1–2 week time-scale of the shipments and interactions they finance and insure.

Trade, particularly international shipping, is sensitive on 2–3 week time-scale of shipments. Real estate and services are sensitive on the planning time lines of customers. Hotels and restaurants are discretionary on even longer time-scales. Construction and furnishing are jointly sensitive to weather on 3–4 week time-scales if efficient reallocation of resources and workers is to be possible. Finally, environmental measurements, publishing, and apparel are sensitive on monthly to seasonal time-scales.

Sector benefits from any sector i can be approximated by a logistic curve

$$B_i = B_{Mi}(1 - e^{-t/t_i}), \quad (1)$$

where i is an index for the sector, t_i is its characteristic time from Figure 5, B_{Mi} is the maximum benefit possible from that sector, i.e., the product of the percentage benefit of Figure 4 and the sector GDP contribution of Table III. Figure 7 shows the cumulative benefit, $\Sigma_i B_i$, as a function of t_i . It rises linearly for benefits of \$10 to 230 B/year, but then turns almost vertical for larger values, which indicates the benefits to longer measurement and prediction times increase proportionally through 2–3 weeks, after which much greater increases in predictions are required to realize the smaller remaining benefits. This sharp increase in slope is due in part to the neglect of the benefits of long time-scale resource, environmental, and climate measurements, which could be of great value, but have not been bounded as yet. In any case, those time-scales are too long to be of interest relative to the half-month to one-month weather forecast improvements of present interest.

Figure 8 displays the dollar benefits of the top ten sectors as function of prediction time. The top curve for trade reaches ~\$25 B/year in one week, \$40 B/year in two, \$48 B/year in three, and continues to grow for all prediction times shown. The second curve for Construction rises more rapidly but saturates at about \$30 B/year after three weeks prediction time. The third curve for Real Estate increases more slowly, but continues to grow for all times. The other curves saturate in similar times at levels determined by the product of their contribution to GDP and percentage benefit.

Cumulative impact. Figure 9 compares the variation of benefits summed over all sectors as a function of prediction time to the approximate form

$$B = \Sigma B_M(1 - e^{-t/\langle t \rangle}), \quad (2)$$

where $B = \Sigma B_i$, $B_M = \Sigma B_{Mi}$, and $\langle t \rangle$ is an approximation to the weighted average of t_i over sectors using the B_{Mi} as weighting functions. The value of $\langle t \rangle$ used is 11 days, which gives ~5% agreement overall, although it rises slightly too slowly for small t and overshoots slightly at $t > 4$ weeks, which is not of present interest.

The computed and approximate benefits increase essentially linearly from 0 to ~\$110 B/year as the prediction time increases from 0 to 1 week. They then increase more slowly from ~\$110 B/year to \$160 B/year as the prediction time increases from 1 to 2 weeks, and from ~\$160 B/year to \$180 B/year as it increases from 2 to 3 weeks. Thereafter, they increase more slowly to ~\$220 B/year after 6 weeks. A forecast of one week's validity is less than a factor-of-two beyond current capabilities, so its significant benefit should be attainable. Two weeks is presently thought to be a reasonably conservative estimate for atmospheric predictability times, so the \$160 B/year is arguably attainable. Reliable forecasts of three weeks validity may be possible, depending on the magnitude of various atmospheric decorrelation times that could be measured by the proposed data-collection system itself. Four to six week forecasts may be possible, but are not really of great economic interest, on the basis of the cumulative benefits indicated.

The Bottom Line. Weather forecasting of a half-month validity could support global economic enterprises ranging from transportation to agriculture. The main requirement is timely dissemination of high-reliability and –precision forecasts. While the foregoing describes potential

benefits on the various sectors of the U.S. economy, the extension to global benefits can, to a first approximation, be estimated by simple multiplication by the ratio of developed geographic areas.

The basis for the assessment of impact is the extent to which economic activity is impeded by unexpected, adverse weather, which groups the economic sectors into three rough classes with major, intermediate, and modest impact. As a percentage of sector activity, the greatest benefits are predicted to be in Aviation because of its fuel, capital, and crew costs; Hotels and Restaurants because of customer discretion; Natural Disasters because of short time-scales and mounting costs; Construction because of its restriction to useful weather; Agriculture because of the tight timing of harvests and processing; and Apparel because of the strong seasonal dependence of sales. Environment, Transportation, Trade, Real Estate, and Insurance show lesser benefits. Remaining sectors show moderate indirect dependences.

Ranking sectors by characteristic time-scale of required forecasts gives a different ordering, with Natural Disasters, Aviation, Agriculture, Textiles, and Entertainment and Recreating at the top; a large number of moderately sensitive sectors in the middle; and a few sectors such as Construction, Home Furnishing, Environment, Publishing, and Apparel requiring the longest-duration forecasts.

These contributions to GDP, fractional potential benefits, and characteristic time-scales can be combined with a set of logistic curves proportional to the product of GDP contribution and percentage benefit that saturate when the forecast duration is large compared to the time-scale of the sector. Summing these curves over sectors then gives the predicted benefits of any given prediction time. The result can be approximated closely by a two-parameter logistic curve in which the first parameter is the total expected benefit and the second is a sector-average time-scale whose magnitude is about 11 days.

The expected benefits increase linearly to ~\$110 B/year for weather-prediction times of one week; more slowly to \$160 B/year for forecasts whose validity-interval is two weeks, and to \$180 B/year for three-week forecasts, all of which should be attainable. Four- to six-week forecasts may be possible, but are not economically compelling, on the basis of the cumulative benefits predicted. The overall benefits of \$100-200 B/year are ~1-2% of the U.S. GDP, which is reasonable on a casual inspection of the sensitivity of overall economic activity to weather disruptions. Global economic benefits may be expected to be about 4 times this level, or \$400-800 B/year, based on ratios of developed areas.

Table III. U.S. economy by sector, forecast economic impact and characteristic time-scale.

Sector	GDP \$B/yr	% Benefi t	Time Scale (days)
Strong Impact			
Agriculture	149.6	10	14
Apparel	32.5	10	14
Banking & Finance	191.9	5	28
Building Materials	62.4	10	28
Construction	274.4	20	14
Energy	299.8	5	28
Entertainment/Recreation	82.8	10	28
Environment	100.0	5	14

Food Processing	106.7	3	14
Hotels & Restaurants	56.8	20	14
Insurance	136.6	5	14
Investment	172.0	2	28
Natural Disasters	100.0	30	14
Paper & Forest Products	48.9	4	14
Telecommunications	197.9	3	14
Trade	1245.5	5	14
Transportation	169.7	3	14
Aviation	72.6	20	14
Limited Impact			
Auto & Truck mfg; parts	121.9	1	14
Chemicals	152.0	2	14
Electrical/Electronics	261.2	1	14
Government	684.0	2	28
Health Care	379.0	2	14
Home Furnishings; appl.	19.7	1	28
Industrial Services	402.2	2	14
Machinery & Fabrication	367.6	2	14
Mining	54.2	10	28
Misc. Services	483.4	2	28
Petroleum Production	86.1	3	14
Publishing	76.7	1	28
Real Estate	814.8	5	28
Textiles	25.7	3	28
Adjustment of GDP	-159.7		
TOTAL	7268.9	365.6	

Atmospheric Transponder Convective Transport Studies. At the present time, existing General Circulation Models (GCMs) models have horizontal resolutions of the order of 1 - 3 degrees in latitude and longitude, 16 vertical levels between the surface to ~3 millibar (mb) pressure-altitude, and time steps of the order of 1000 seconds. Regional prognostic models have horizontal resolutions on the order of 1-10 km, 40 vertical levels between the surface and ~ 15 km altitude, and time steps of the order of 5 seconds. The current model development strategies are just beginning to take advantage of massively parallel computer architectures. The USDoE and LLNL, via their advanced Environmental Science and Computing initiatives, are attempting to close the resolution gap between the regional and global models by supporting the development of the next generation of very high resolution global models; LLNL's Atmospheric Science Division is currently using the NCAR (National Center for Atmospheric Research) CCM3 GCM as well as the NRL (Naval Research Laboratory) COAMPS Regional Prognostic Model for application studies in the area of global climate change and regional studies of the atmospheric transport and fate of hazardous materials. These models are being ported to the current ASCI machines.

Initial systems studies will be performed to aid the transponder development team in the systems planning for optimal transponder insertion, location, drift, and lifetime scenarios.. We will be working with the global model development teams (LLNL-LANL-NCAR-NASA) to use the next generation of very high resolution GCMs, as they become available, for advanced systems studies. We will also work with groups at NCEP and NRL to coordinate efforts in the application studies of the use of high resolution observational data-sets in numerical weather prediction schemes.

Daley cites two conditions which must be satisfied to provide a successful prediction of a future atmospheric state:

- I. The present state of the atmosphere must be determined as accurately as possible.
- II. The governing equations and laws of physics from which future states develop from preceding states must be known.

Daley discusses the international weather observational system as it existed in 1989; it exhibits large areas of the globe with sparse observational data collection features. Satellite-based temperature measurements have resolutions on the order of 250 km horizontally, 200 mb in altitude (~2 km near the surface to ~7 km at the tropopause) and temperature errors of 2 – 3 Kelvin. Our currently proposed spatial resolution is ~0.3 km vertically , ~10 km horizontally, and errors of ~1 K. Present surface station observations are *irregularly distributed* over land and well-traveled shipping lanes and provide temperatures to 1 K accuracy and horizontal winds to ~3 m/s accuracy. High altitude (~200 mb) wind observations, obtained by aircraft and satellite-generated cloud-drift data, and low altitude wind observations are *irregularly spaced* and have accuracies on the order of 3 - 5 m/s. Our proposed wind data resolution is ~0.3 km vertically , ~10 km horizontally, and errors of ~1 m/s. Lorenz and Emanuel show that, for simplified models, significant increases in the 5 - 10 day "forecast skill" can be made by increasing the observational data base in sparsely sampled regions. Our proposed global, regularly-spaced, high resolution observational database should provide enough coverage to yield data over the sensitive areas which currently limit forecast accuracies.

Lorenz considered the issue of the predictability of the atmosphere and concluded that the range of predictability of the atmosphere, given the accuracy in the observations of the state of the atmosphere at that time and the details of the prognostic models, is about two weeks. A quarter-century ago, one of us (CEL), using estimated observational resolution achievable in the 1980s, developed a Monte Carlo procedure which improved forecast skills of the models in the 6-10 day range. Holton concludes that the meteorological community has expectations of useful forecasts of the detailed structure of the general atmospheric circulation for periods out to between 7 and 14 days. Ensemble model forecasting techniques allow skill scores of between about 20% to 70% for forecast lengths of up to two weeks depending on the area, season and forecast variable. (Skill scores are defined as 100% for perfect forecasts and 0% for forecasts which are only as good as the reference climatology.) Adaptive adjoint model techniques applied to NWP (numerical weather prediction) models result in skill scores on the order of 10% to 70% for 5-10 day forecasts of the 500 mb geopotential height over the Northern Hemisphere. The next generation of climate models, currently being developed, will have ~10 km horizontal resolution and ~40 vertical levels as well as a coupled ocean model. This increased resolution over the current generation of NWP models will allow inclusion of more detailed, smaller-scale processes and should provide improved forecasts in the 1-14 day duration-of-validity range. Further improvements in computing power will allow higher model resolutions; such improved model capabilities, when coupled with the proposed observational data base, can reasonably be expected to yield substantially increased forecast skill scores in all regions of the globe.

Studies are required to determine insertion requirements, spacing, and evolution of the atmospheric transponder ensemble. In order to perform these studies, numerical models which provide realistic global weather pattern simulations must be utilized. This requires the use of a global circulation model (GCM) to provide atmospheric wind flow patterns coupled to a transport model to generate long-duration trajectories of individual transponders. Transponder insertion scenarios can then be studied to provide optimal insertion locations and rates, as well as resulting ensemble distribution, and spacing data.

The first issues addressed in a scoping study by two of us (AG and CM) to these ends were

1. Will an initial, uniform global distribution of transponders retain reasonably good global coverage after a thirty-five day time-interval, corresponding to $\sim 4\pi$ of trajectory-wrapping around the Earth?
2. Will a vertical line-release of transponders at a set of selected launch sites provide a reasonable global distribution of transponders after the reference thirty-five day time-interval?

Our initial studies have employed the NCAR CCM3 GCM to provide the horizontal wind fields at each grid point of a $2.8^\circ \times 2.8^\circ$ (latitude-longitude) \times 18 vertical level global grid at four-hour time-intervals over a period of 35 days. The wind fields were used to drive the LLNL GRANTOUR chemistry-transport model; GRANTOUR is a Lagrangian parcel model in which the atmosphere is treated as a set of constant-mass air-parcels advected by GCM wind fields on a fixed Eulerian grid. For the simulations of present interest, each parcel was taken to be a transponder and parcel chemistry was turned off. The above grid gives 8192 transponders at each vertical level. For these initial studies, we assumed that the transponders are constrained to fixed pressure-altitude levels and their vertical motions therefore are neglected. (Sample calculations based on the equation of motion given by Hanna and Hoecker for small, high drag-coefficient balloons of the type we envision for our atmospheric transponders indicate that they should be tightly coupled to the designated pressure levels, even for relatively large vertical air velocities.)

The results of our study of the first of the two issues just cited are shown in Figures 10-12. Figure 10 shows the initial, uniform transponder distribution at each σ level ($P/1000$ mb) in the model atmosphere. σ levels of 0.925, 0.775, 0.6, 0.4, and 0.2 were used in the calculations. Figures 11 and 12 show the transponder distributions at $\sigma = 0.775$ (~ 1.5 km altitude) and 0.2 (~ 11.5 km altitude), respectively, after 35 days. These results indicate that the 35-day transponder distributions still provide reasonably global coverage.

The results of the study of the second issue cited above are shown in Figures 13-15. A suite of 306 transponder launch sites were chosen to provide a global coverage with the condition that there be a land mass available at the site for a launch platform. Figure 13 shows the map of launch sites. At each launch site, transponders were released at a rate of 1 transponder per day, at each σ level, over the 35-day time-interval of the model study. Figures 14 and 15 show the transponder distributions at $\sigma = 0.775$ and 0.2, respectively, after 35 days. The Figures indicate that the 35-day transponder distributions provide reasonably global coverage, similar to that calculated in the studies of the first issue.

The transponder trajectory calculations performed in this paper can be compared to actual balloon trajectories measured by the GHOST Balloon Project. A series of 200 balloon flights were made in the Southern Hemisphere with super-pressure balloons at altitudes of ~ 900 mb to ~ 30 mb.

A set of trajectories were given for a 200 mb altitude balloon launched from Christchurch New Zealand. The trajectories for 8 orbits are approximately circular and have an average period of about 12.5 days. As a validation of the CCM3-GRANTOUR balloon trajectory model, a calculation of 200 mb balloon trajectories were made for a balloon launched from Christchurch. The result is shown in Figure 16. The average orbital period for the calculated balloon trajectory is approximately 10 days and the extent of the orbits is in good agreement with the experimental results. In addition to the trajectory measurement, a set of atmospheric balloon lifetimes were given and are reproduced in Table IV.

Table IV. GHOST Project Balloon Lifetimes

<u>Altitude (mb)</u>	<u>Lifetime (days)</u>	<u>Life-Limiting Factor</u>
700	~14	super-cooled water accumulation
500	7 - 10	super-cooled water accumulation
400	~15	super-cooled water accumulation
300	30 - 40	ice crystal accumulation
200	~150	ice crystal accumulation

These data, along with the CCM3 GCM convective and large-scale precipitation fields, can be used to develop a transponder lifetime parameterization which could be incorporated into subsequent model studies of transponder transport and lifetime.

We anticipate that future transport simulation scenarios will include (1) extension of the above calculations to a full annual cycle; (2) incorporation of large-scale vertical velocities derived from the CCM3 GCM horizontal velocity fields, coupled to a parameterized transponder equation of motion, to allow simulation of the effects of surface release of the transponders and vertical motions on the resulting global transponder distributions; (3) finite transponder lifetime effects; and (4) localized transponder dispersion effects using nested CCM3-COAMPS (a regional prognostic model) wind-fields.

Another crucial study will improve our understanding of how different distributions of the transponder ensemble will affect forecasts. We envision taking a GCM run over a period of time of two weeks as a “truth” simulation. The next step will be to perform simulations of the kind performed by Lorenz and Emanuel, for a simple atmospheric analog in which full GCM forecast runs would be made for cases which have varying degrees of incomplete initial grid-point data. The object of these studies will be to determine the dependence on the population-size and the positioning of transponders of the generation of forecasts with specified skill scores. These exercises will enable cost-benefit trade-studies involving transponder numbers and deployment scenarios. As in the cases discussed above, initial studies will be made with the CCM3 GCM and advanced studies will be performed with the newer high resolution GCMs currently being developed. We will also address the question of whether increases in resolution of the GCM models change the optimal systematic and requirements on the transponder ensembles which were calculated using lower-resolution models. Increased model resolution will lead to more detailed models of small-scale processes which, in turn, may change the prediction capabilities of the forecast models, in turn likely leading to increased data-resolution requirements.

The atmospheric data collection system which we contemplate will require a new look at optimal data assimilation techniques for the next generation of NWP models, given the uniquely high

rates of data to be collected and the model initialization requirements. We expect to establish collaborations with groups at NRL as well as NCEP (National Center for Environmental Prediction) to determine the best methods for data assimilation, ones which will most efficiently use the high resolution data collected.

Transponder Basic Lifetime And Performance. One of the key features of the type of weather-forecasting system which we contemplate is a large set of "atmospheric transponders" which are interrogated by a constellation of Earth-orbiting satellites, and which report back – directly or implicitly - to the interrogating satellite on salient local atmospheric conditions, e.g., vector position, vector wind-speed, temperature and relative humidity. For reasons of basic practicality, these transponders must be inexpensively implemented, must have suitably long lifetimes and must have acceptable environmental side-effects – in addition to functioning with adequate precision and system-level reliability.

It wasn't entirely clear at the outset that all of these conditions could be simultaneously satisfied with current technological means. Considerable progress has been made during the past year in these respects, although much remains to be done.

Studies by some of our Los Alamos colleagues has established that children's balloon technology is indeed suitable – with minor enhancements – as a base for these transponders, in that they may be readily made to have lifetimes against buoyancy loss which is long compared to their currently-estimated lifetimes in the 'real' atmosphere, just discussed. Though we have yet to actually demonstrate it, we remain confident that these very readily realized structures can be made to report local temperature via DIAL-type laser interrogation, e.g., of an internal reflector coated with low-band gap semiconductor. We have yet to identify a comparably simple means of sensing and reporting-under-interrogation the local relative humidity, although we remain confident of our ultimate ability to do so. High-precision sensing of each transponder's vector position and vector velocity is of course an intrinsic feature of our system design.

Considerably more challenging from the present vantage-point is the issue of interrogating the transponders when they are more than a few optical depths below the tops of cloud systems. In such circumstances – which are regrettably prevalent in the lower troposphere – the baseline transponders are effectively "out of touch" with the satellite constellation overhead; we simply can't generate sufficient link margin with our baseline optical communications/interrogation system to "punch through" the scattering opacity of the intervening water/ice particles. Our present, still quite tentative approach is to provide at least a subset of lower-altitude atmospheric transponders with an ability to respond at microwave frequencies to satellite interrogation, although the most-preferred specific design is still being debated. From a standpoint of simplicity and economy, it would be preferable to not admit the presence of stored energy or even of a single *ad hoc* chip energized by the interrogating beam within the transponder, but it isn't clear that adequate transponder performance could then be realized under the most adverse circumstances, e.g., deep within a nighttime cloud system. Even a tiny, single, continually-powered chip, of course, solves all problems most readily, but the power supply seemingly poses significant issues from both economic and environmental side-effects standpoints. This issue set is still a quite open one.

We continue to regard global cellular telephony as the most appropriate base for the subset of transponders deployed on the Earth's land and water surfaces which is tasked with periodically reporting pertinent conditions on the ground and in the upper ocean.

Very Large-Scale Computing Systems. Very large-scale computing systems are a *sine qua non* of long-range weather prediction, as we noted in our original proposal last year, to which we refer with respect to all details. We estimated then that aggregate computing rates of 10^{13} - 10^{14}

Floating-point Operations Per Second, or 10-100 teraFLOPS, would be necessary-and-sufficient for generating two-week validity global weather forecasts; these scoping estimates haven't changed.

We also noted a year ago that the Advanced Strategic Computing Initiative (ASCI) of the U.S. Department of Energy is currently spending about \$0.5 B/year in order to realize 100 teraFLOPS aggregate computing capabilities in each of several distinct computing systems by 2002, and that this effort had already attained the 3 teraFLOPS single-system performance level. (It's worth noting in passing that roughly 10% of the total time-averaged capabilities of all of these ASCI systems is being made available to the academic community via the ASCI Alliance, for "basic supporting research" purposes.) Thus, computing systems of the requisite scale and features – e.g., aggregate processing rates and memory capacity, interprocessor communications bandwidth and latency, etc. – rather assuredly will exist, well within time-scales of interest for present purposes.

Emphasizing the rational basis for this optimism is the realization, during the past four months, of a first-of-a-kind "hyper-computing system," one synthesized from $\sim 10^6$ individual computer systems connected to the Internet by the Search for Extraterrestrial Intelligence (SETI) consortium. This system currently performs about 8 teraFLOPS of processing, in the time-average, on radio-astronomical data-sets; pending software enhancements will increase this average processing-rate to roughly 20 teraFLOPS. Curiously enough, this system – whose number-crunching scale likely is just-sufficient for two-week global weather forecasting of the type which we consider – was created at essentially zero cost by a handful of individuals working within a small private organization within a time-frame of a single year, and is literally dependent on the continuing charity of the "denizens of the Internet" to donate the "copious free time" of their individual computer systems. Something of the order of one percent of all Internet computers currently run the SETI "screen-saver," which is actually an attractive and information-rich albeit low-overhead facade for the astronomy data-processing package, presented in lieu of the more familiar "flying toasters" and other such "eye candy." (This initial "hyper-computer" may have comparable significance for many classes of large-scale computable problems as did the advent of the first flowering plant for terrestrial vegetation: it elegantly solves a most serious 'personal problem' – more efficient/successful reproduction – by attracting 'strangers' to its vicinity and 'bribing' them to contribute some of their spare resources to its ends.)

It's not clear – as it hasn't been seriously studied, to our knowledge – that relatively very "loosely coupled" hyper-computers of the SETI type are suitable for long-range weather prediction. However, it may well be that such a network of individual computing systems could perform usefully in such finitely-differenced parabolic differential equation-integrating applications, even though most of them can communicate currently only over $<10^5$ bit/second data-links (i.e., over 56 kilobit/second telephone modems), moreover with communications latencies of seconds (determined by time-lags involved in accessing dial-up-type Internet Service Providers). It's certainly a prospect worthy of serious consideration, as it potentially offers a thoroughly novel, entirely government-independent route to very near-term realization of the requisite computing capabilities for long-range weather prediction – *and* there's currently ~ 1000 teraFLOPS of *unused* computing power connected to the Internet.

Current Observing System Scale Estimates. In the proposal which we tabled at last year's Seminar, we very conservatively scoped both the population of atmospheric transponders and the mean rate at which each transponder was interrogated by the satellite constellation overhead. We have since taken a somewhat more realistic look at just what's required in both of these system-scaling respects. We suggested a year ago that sampling the entire atmosphere, from essentially sea-level up to 30 km altitude with a vertical resolution of 0.1 km and a mean horizontal resolution of 3

km would certainly be sufficient for purposes of two-week duration, high-precision and –reliability weather forecasting. Our current expectation is that sampling at about 30 km horizontal resolution and 0.3 km vertical distance should be sufficient. Furthermore, we presently expect that interrogating each transponder every 8 hours – rather than every 45 minutes, as we proposed last year – should be adequate for our present purposes. The total number of transponders thus has decreased from $\sim 1 \times 10^{10}$ to $\sim 3 \times 10^7$, and the number of satellites required to perform the transponder interrogation task has decreased from 100 to 8.

This order-of-magnitude decrease in satellite population makes it readily feasible to build this modest constellation “by hand,” rather than to first develop and then exercise a production line. The end-to-end cost savings likely aren’t large – certainly considering the enormous benefit-to-cost ratio of the weather-forecasting system – but the potential savings-in-time until the full-scale system can be put into operation are quite substantial.

The two-and-a-half orders-of-magnitude reduction in transponder population undeniably improves the basic practicality of the proposed system, the more so as our initial estimates of a 10^7 second average lifetime for the transponder population are now known to be optimistic for the lower pressure-altitude deployment-fraction due to operation of tropical rain-out mechanisms, as we noted above. Net, however, we expect to decrease the mean transponder deployment rate to at most 10^2 /second, from our initial value of 10^3 /second, with corresponding savings in the scales of the necessary equipment and material feedstreams. However, it seems clear that we will need to deploy the transponders from several tropical locations, in order to most efficiently fill-in transponder population depletions in the great tropical tropospheric circulation gyres.

Summary And Conclusions. If the present interglacial epoch had been of the average duration of the past several, it would have ended about the time that the Great Pyramid was being erected in Egypt – and it’s possible that humans of what we now term the Holocene would have left behind not many more relics than did our ancestors who lived in previous interglacial epochs. Presently, we still have *no* generally-accepted idea of why the present interval of “climatic grace” has extended for as long as it has – or of why it will end, or of when – absent human intervention. We merely know that we live in uncommonly good climatological times, ones which have prevailed less than 10% of the past two million years. Furthermore, we now know that “in life, we are in the very midst of death,” climatologically speaking, for the recently-read geophysical record of the most recent 150 millennia informs us that swift-onset, large-scale “climate failures” were a not-uncommon feature of the most recent interglacial epoch, the only one for which a high-resolution “reading of the record” currently exists; if one of these full-scale “cold snaps” were to commence today, it might kill-via-starvation a substantial fraction of the human race over the next quarter-century.

At that, we humans complain more-or-less unceasingly about our ignorance of the future state of our local microclimates on time-scales of several days to a few weeks, let alone our ability to control this future state. Indeed, such ignorance *per se* is not only tedious but actually seems to impose at the present time an all-sources *per capita* economic cost of the order of \$1 per week, averaged over a year and over the entire human race – an annual loss of at least $\$3 \times 10^{11}$, in a world in which a human life has a geography-dependent current economic valuation of $\sim \$3 \times 10^4 - 3 \times 10^6$. All this is over-and-above the thousands of lives lost in the annual-average due to inability to forecast unusually heavy precipitation over future intervals of 1-2 weeks.

These considerations have motivated our studies of ways-and-means which are practical at the present time of reliably preventing large-scale climatic excursions, especially those which might occur quickly, and of predicting the weather in detail over half-month intervals into the future, respectively. When we first reported these prospects, during the past few years, they hadn't seen either a great deal of quantitative assessment or significant peer review. The fundamental change since then is that both of these deficiencies have been remediated significantly – and that the basic technological feasibility outlook for each is as at least as good as when first reported.

Specifically, purposeful-and-rational forestalling of the onset of climate catastrophes continues to appear to be feasible to execute, in the global annual space- and time-average, by modulating either the insolation or the mean albedo of the Earth. The result is no more than conservation-of-energy in the terrestrial thermodynamic context, but the means, slightly remarkably, appear quite readily attainable, moreover along each of several technologically independent axes. Most remarkably, perhaps, simple subtraction of insolation, e.g., by use of stratospheric scatterers of sunlight, has very recently been model-predicted to rather exactly offset the model-predicted mesoclimatic effects, direct and indirect, of elevated atmospheric CO₂ concentrations during the next century. In other words, changes in temperature throughout the biosphere, both geographically and seasonally, are predicted to be offset reasonably precisely simply by removing of the order of 1% of incoming sunlight. While such predictions necessarily aren't entirely dependable, given the limitations of present models and of the computer systems which host them, they logically demand respect comparable to those of predictions of global change *per se*, for exactly the same means were used to create them both.

Also, means of sampling the salient properties of all relevant portions of the Earth's atmosphere sufficiently precisely to support rational, quantitative, reasonably precise weather prediction over half-month intervals have been studied in first-level detail, and have been found to be as apt as initially suggested. Atmospheric transponders based on durable balloons implemented with modern materials have been shown to have lifetimes against loss-of-buoyancy which are substantially greater than the intervals which other, model-based studies have determined is the effective "lifetime in the atmosphere" for such objects. Quite importantly, these latter modeling studies have also determined that the "regional clumping" and "regional depopulating" effects of atmospheric circulation on transponder populations do not occur at "show-stopping" levels and, indeed, may be effectively managed with the same system regeneration means which address finite transponder lifetimes against rain-out and icing mechanisms. Collaterally and quite independently of our own endeavors, an Internet-implemented "hyper-computer" has been demonstrated-in-operation during the past several months, one whose raw number-crunching capabilities-in-the-aggregate are far in excess of that needed to process the satellite-derived atmospheric data and thereupon generate the desired long-range, high-fidelity weather predictions.

At that, both of these enterprises must be considered to be still in their very early stages. With respect to long-range weather forecasting, atmospheric transponders of the type we contemplate having both temperature and relative humidity-reporting capabilities have yet to be prototyped, and brassboard-level satellite instrumentation for high-rate interrogation of these transponders has yet to be fielded; these are obvious near-term milestones to be attained. Transponder lifetimes in the 'real' atmosphere hasn't been experimentally established at any pressure-altitude (although GARP data-sets provide useful bounds for scoping purposes), and the feasibility-in-principle of long-term weather predictability is still a subject of some technical debate. With respect to forestalling climate changes, experimental studies necessarily are still nonexistent, for the ethical and legal bases of such

endeavors have yet to be laid. Nonetheless, we expect that such geoengineering experimental work in small sub-scale – perhaps inducing completely imperceptible mean global temperature changes of a dozen millikelvins – might be able to get underway within a half-decade, moreover at costs which are several orders-of-magnitude less than the current $\sim 4 \times 10^{11}$ annual global primary-energy budget. We continue to be intrigued by the fact that the economic benefits to humanity from such applied research – ~ 300 B/year – are potentially larger than that of any other technological endeavor known to us, that the payback-time for the associated billion dollar-scale investment required to create the weather-predicting system is of the order of 1 day, and that the initial sub-scale research apparently is so inexpensive that it is well within the capabilities of a private foundation.

We look forward to reporting progress along these – and related – lines in subsequent sessions of this Seminar.

Acknowledgments. We are grateful to many colleagues – only a very few of whom are explicitly referenced in the text – for previous results and for useful discussions. As was also declared previously, we make no claim, explicit or implied, for originality of any of the concepts or specifics presented in this paper, many of which may be due to others, in either the present or some similar form.

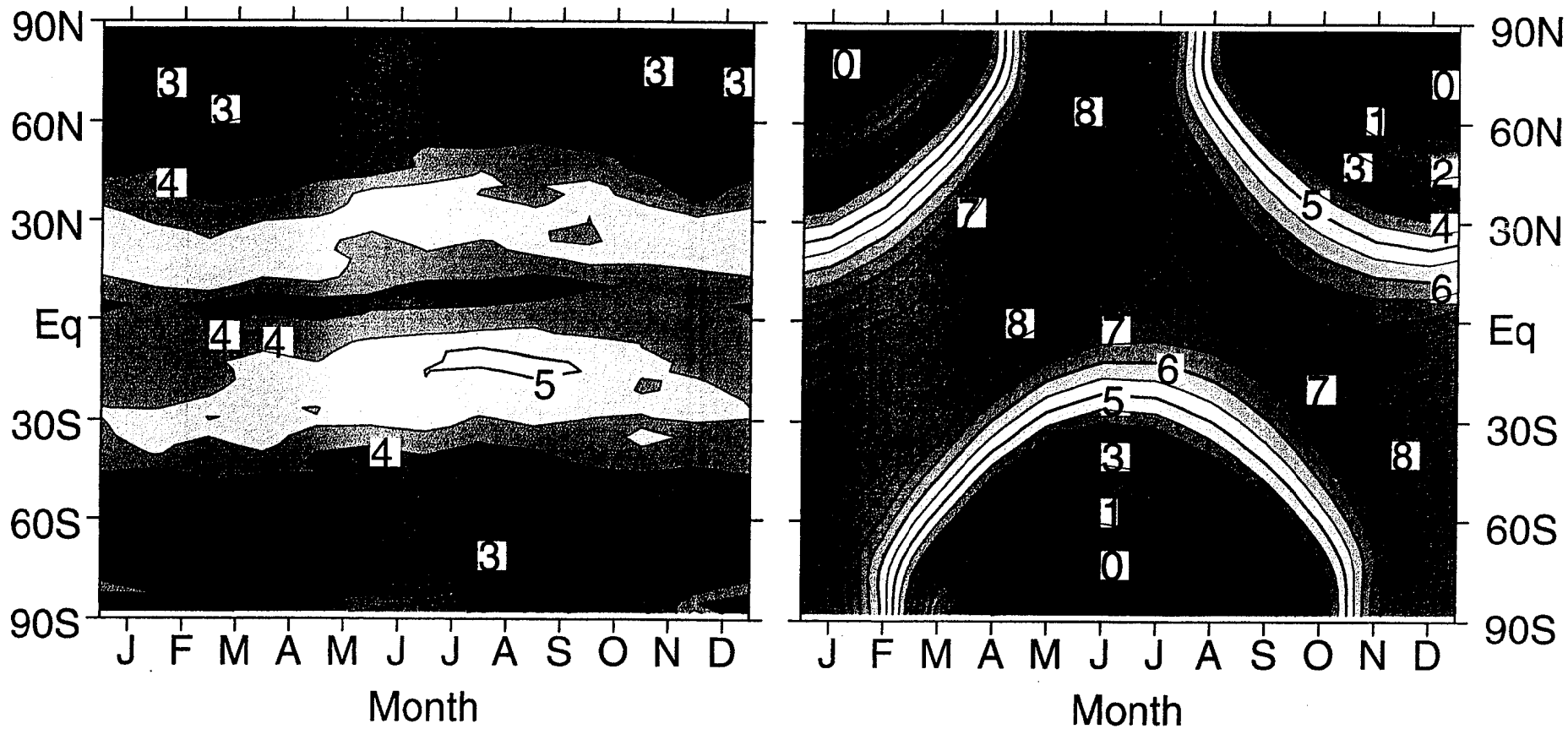


Figure 1

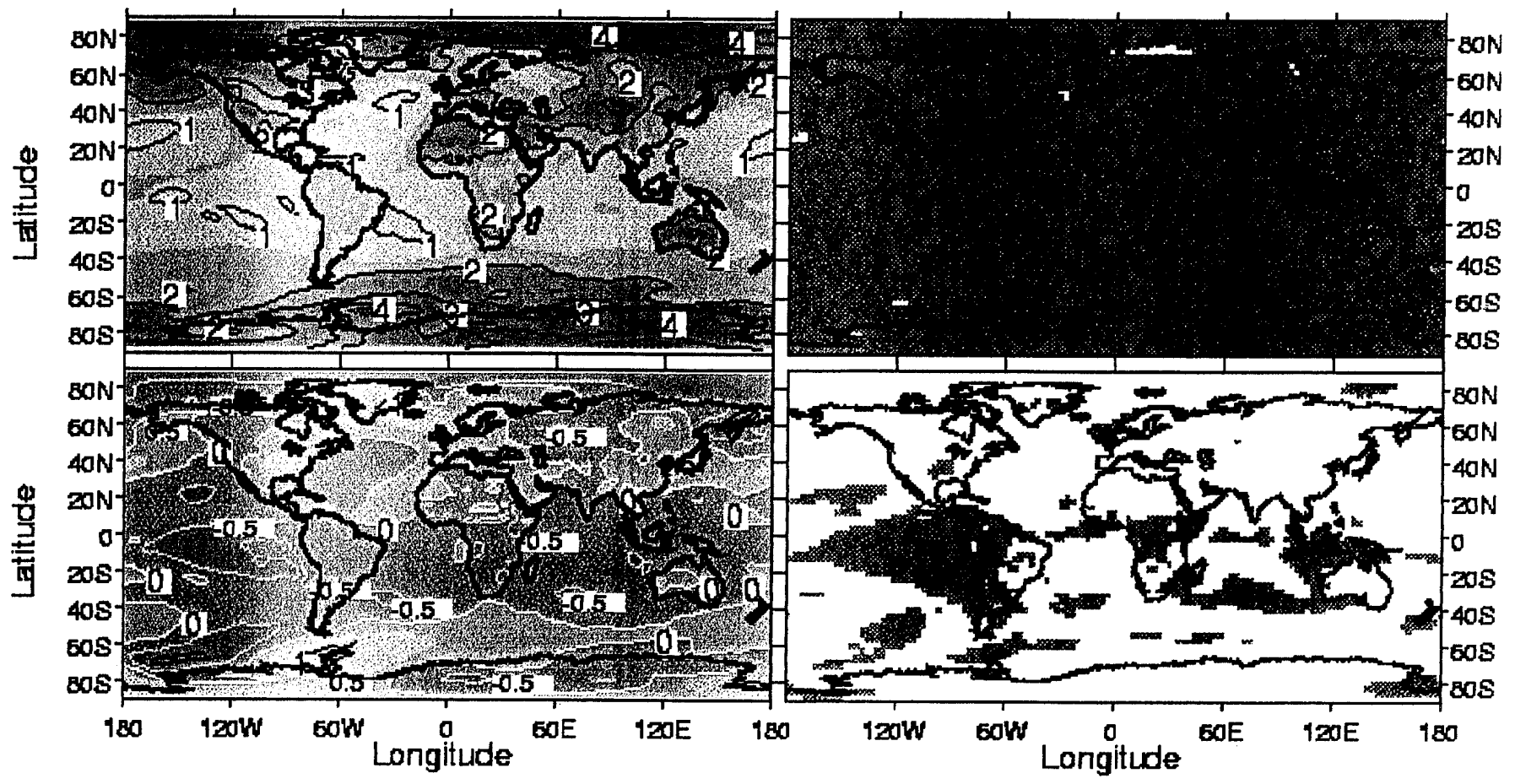
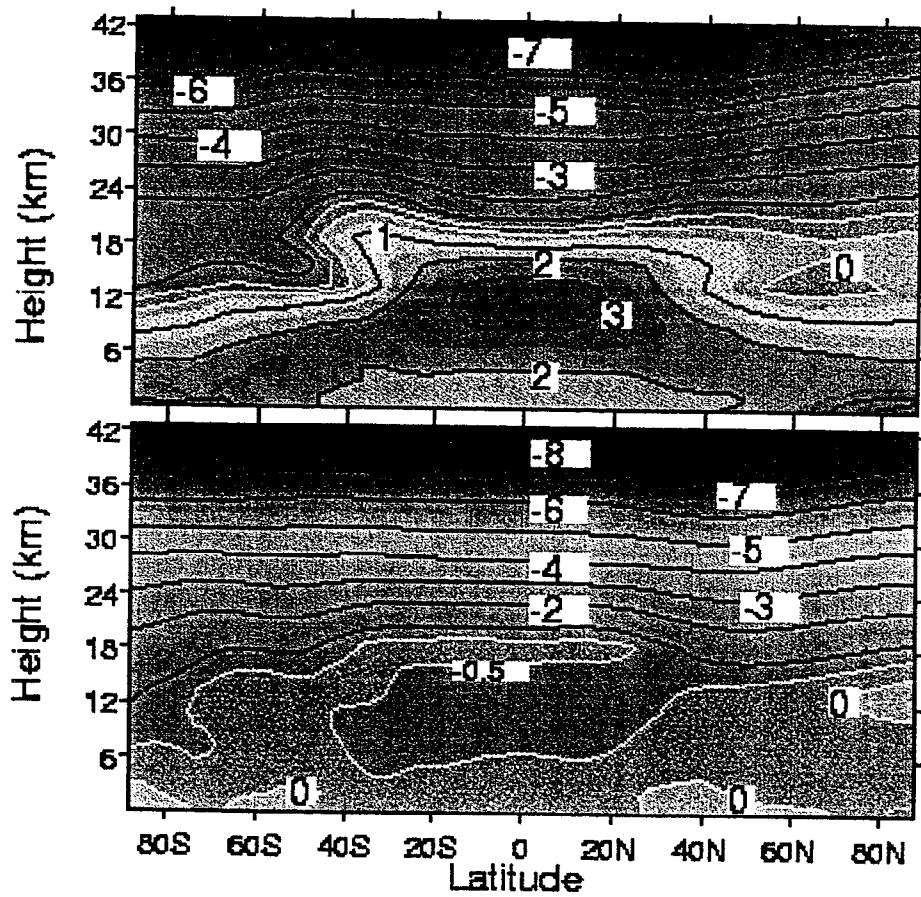


Figure 2

Figure 3



Estimated % Benefit vs sector

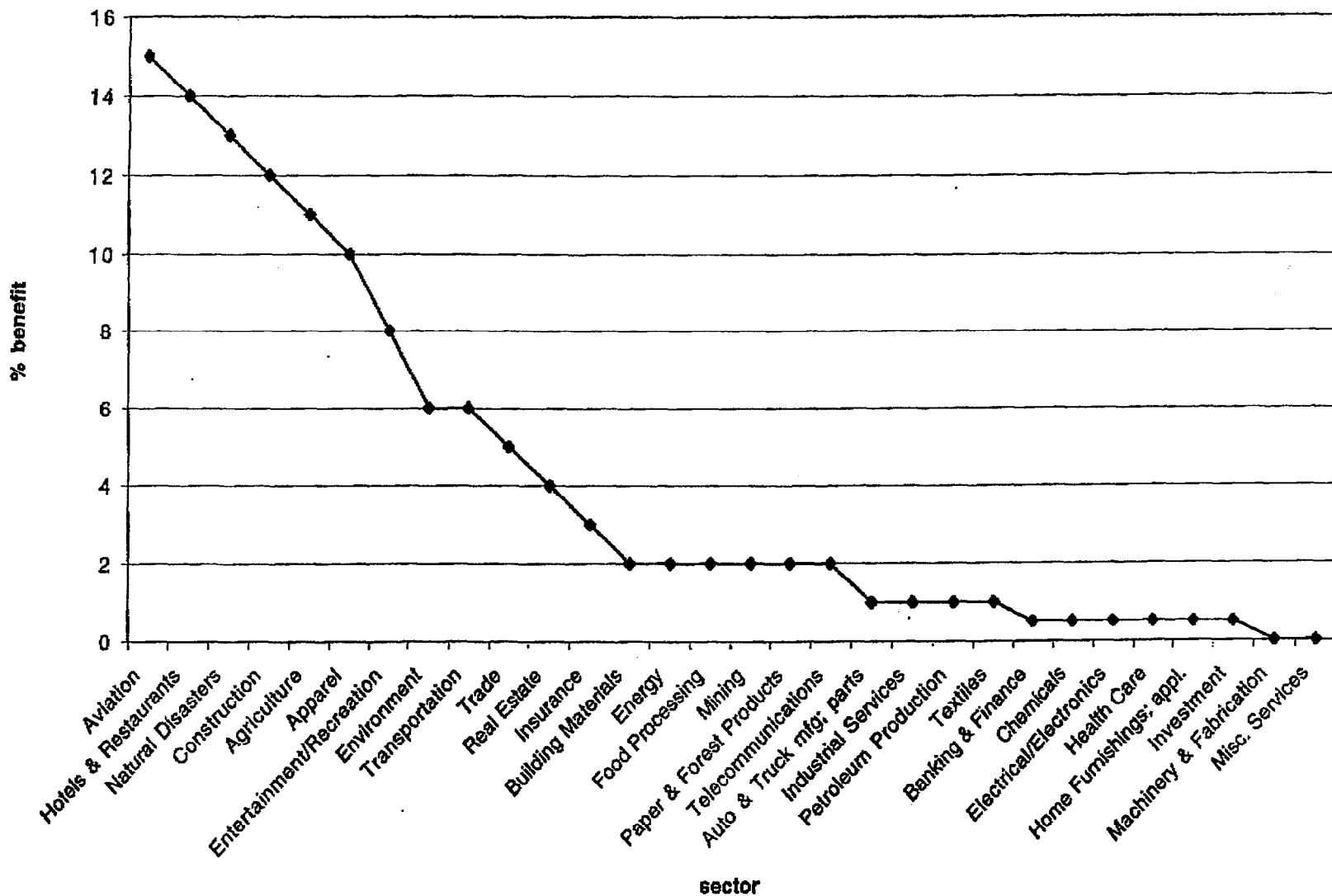


Figure 4

cum & impact vs sect

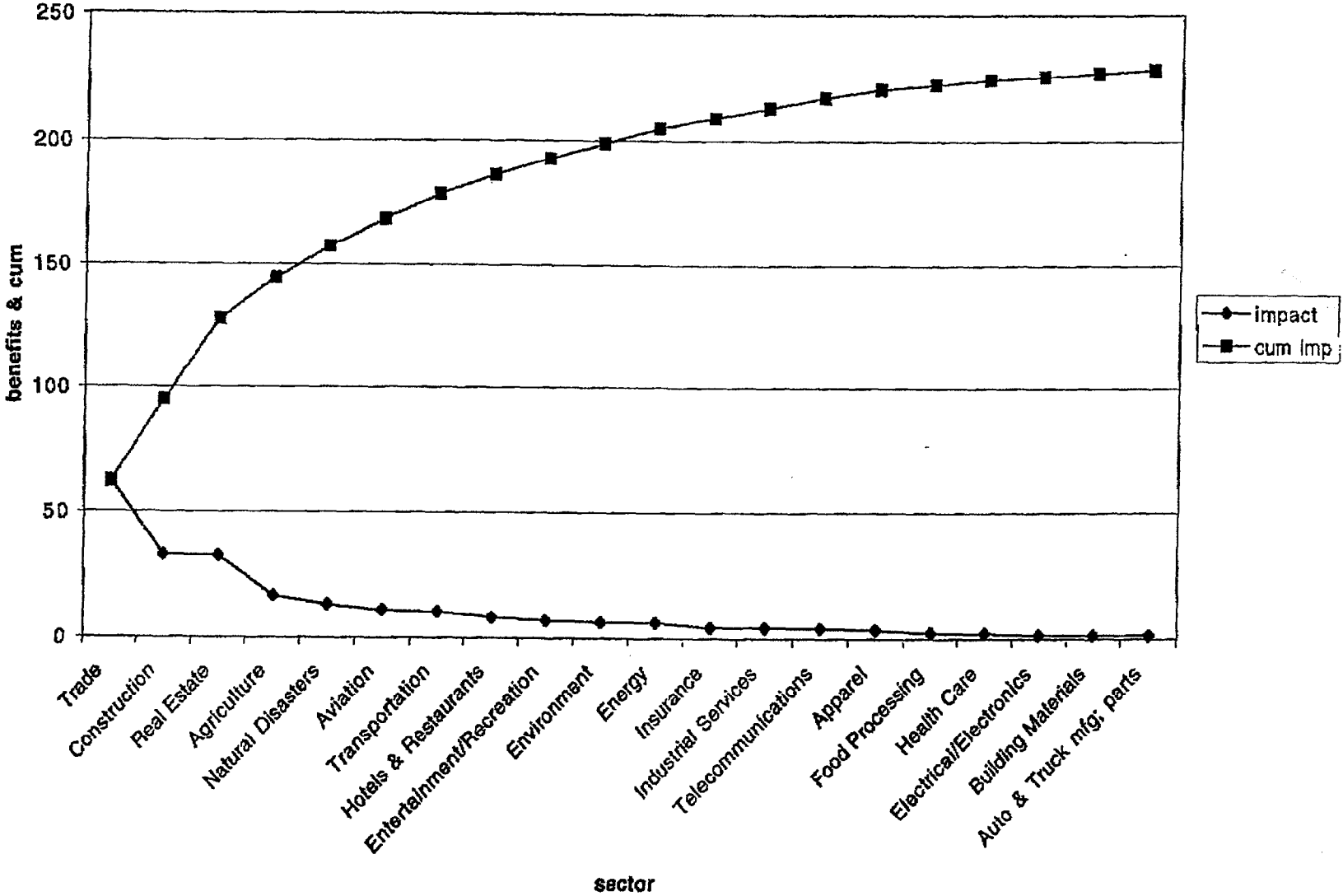


Figure 5

Time Scale vs sector

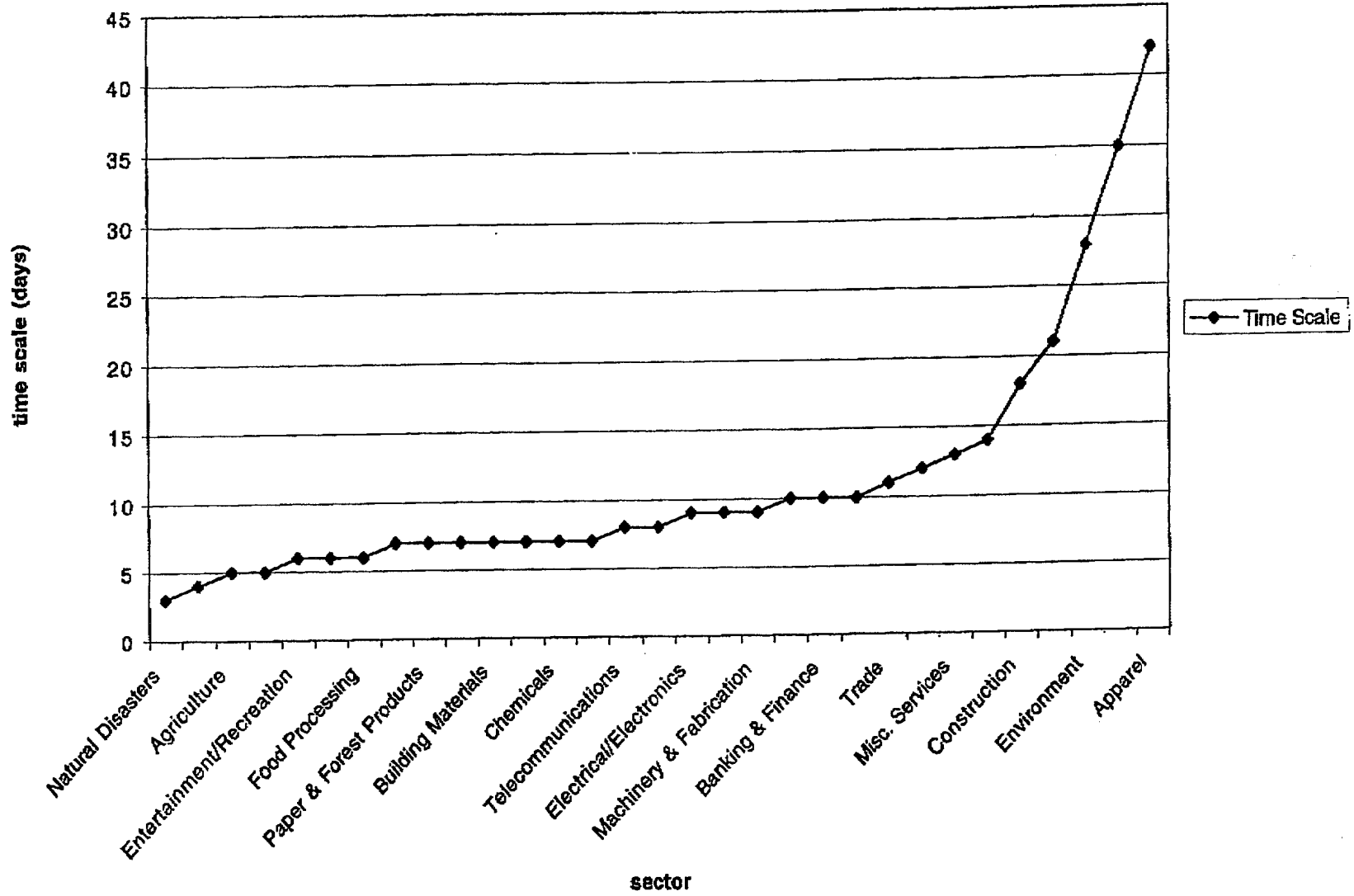


Figure 6

Time Scale vs cum Impact

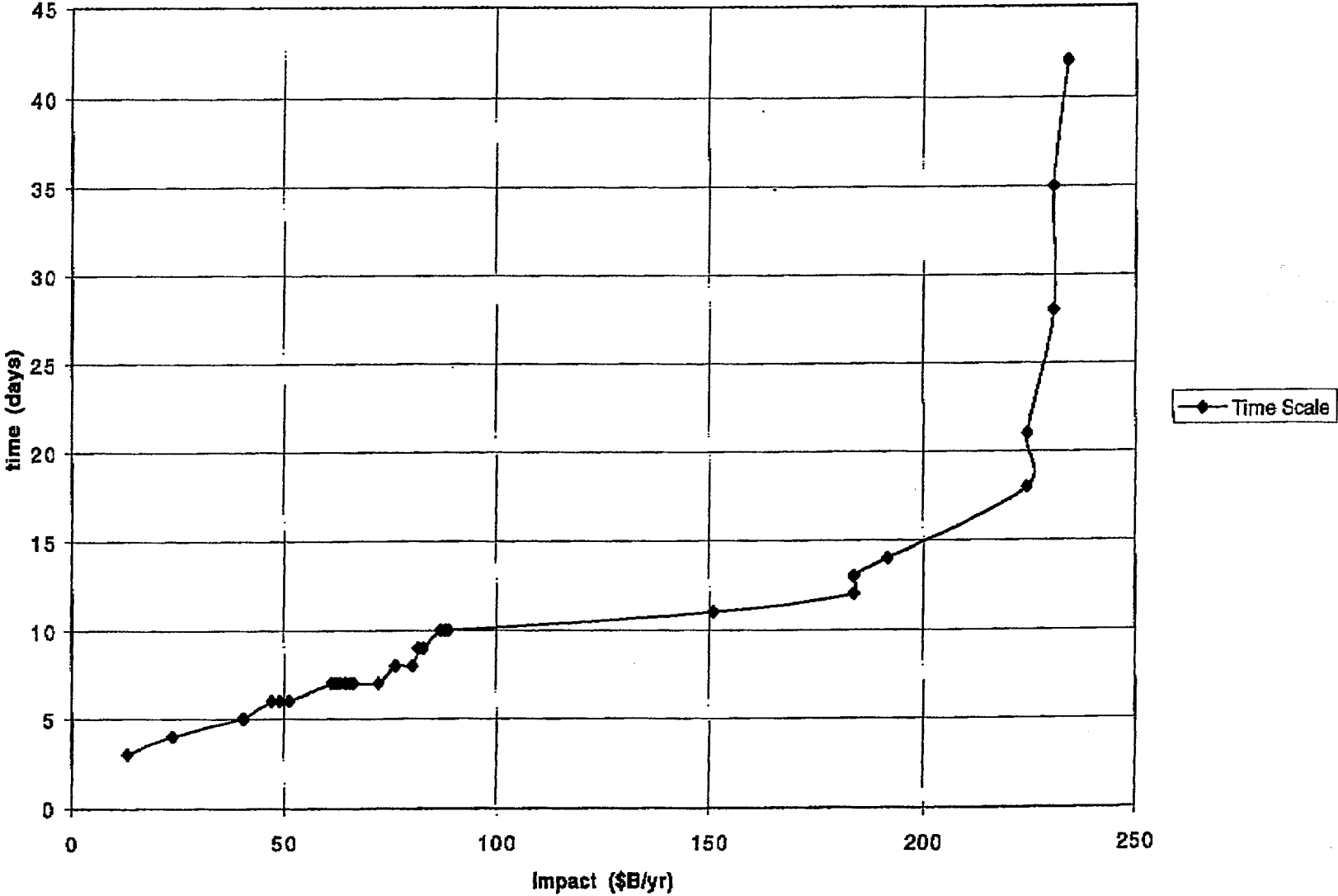


Figure 7

Sector benefit vs time

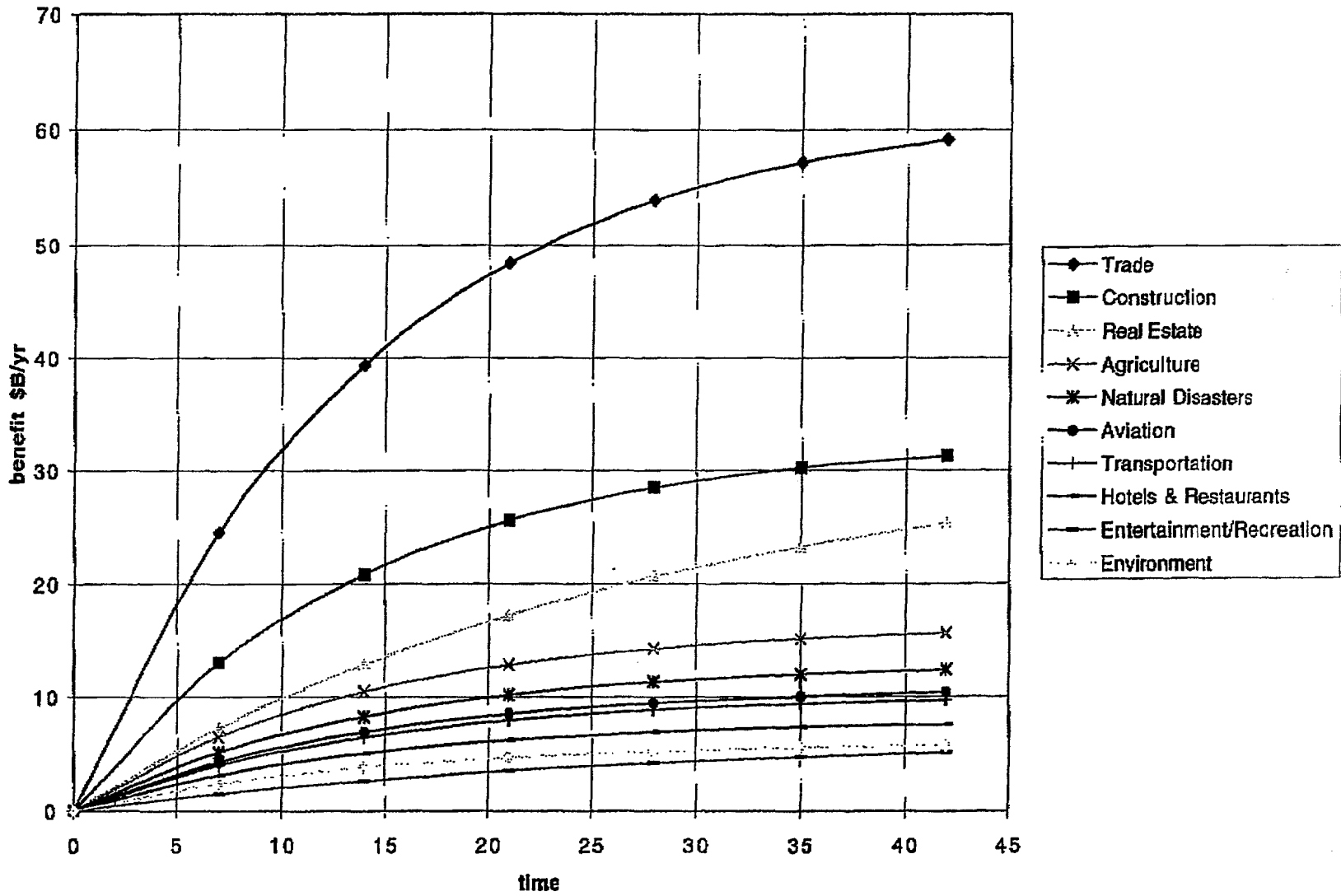


Figure 8

Actual and approximate benefits

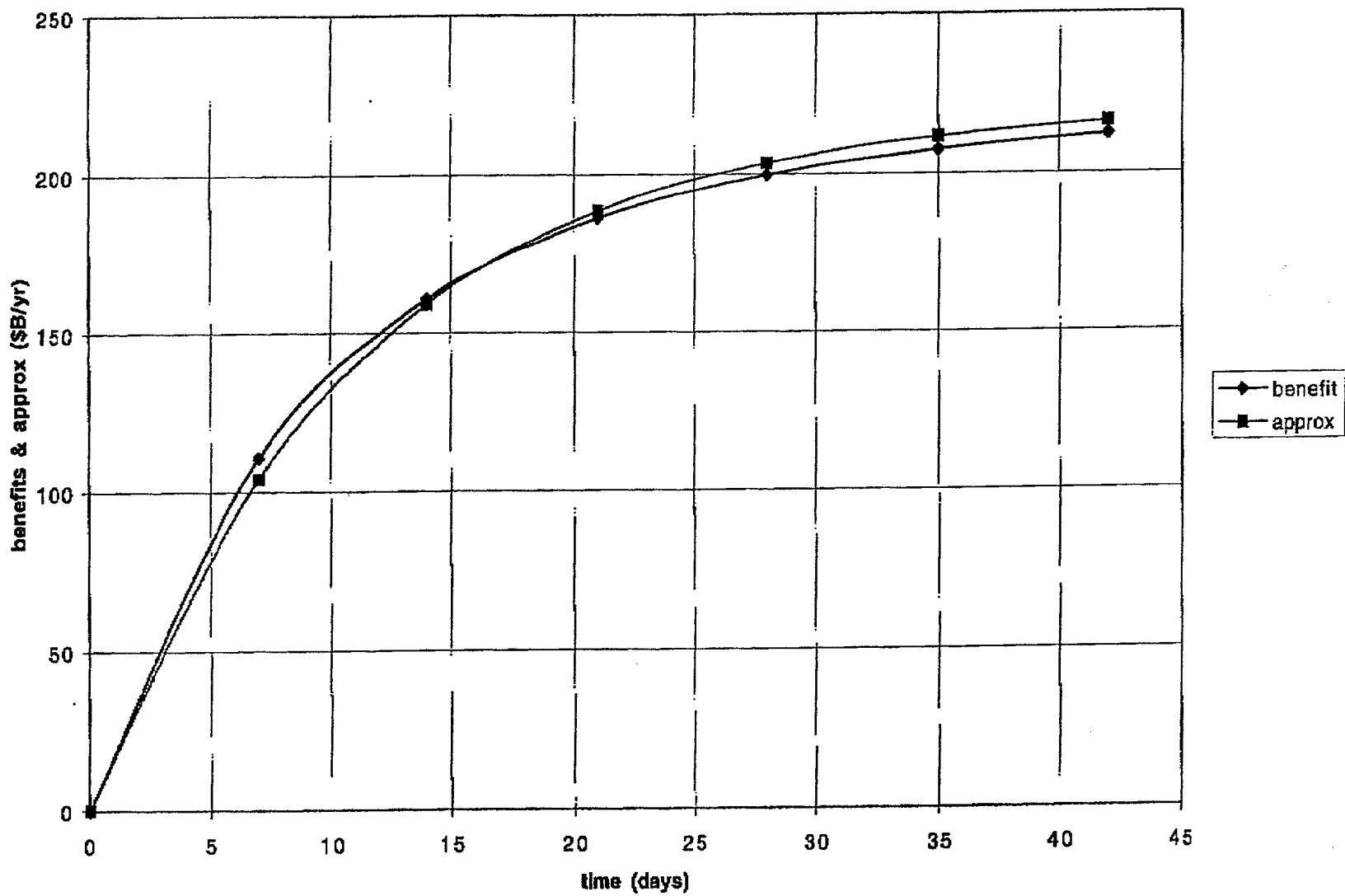
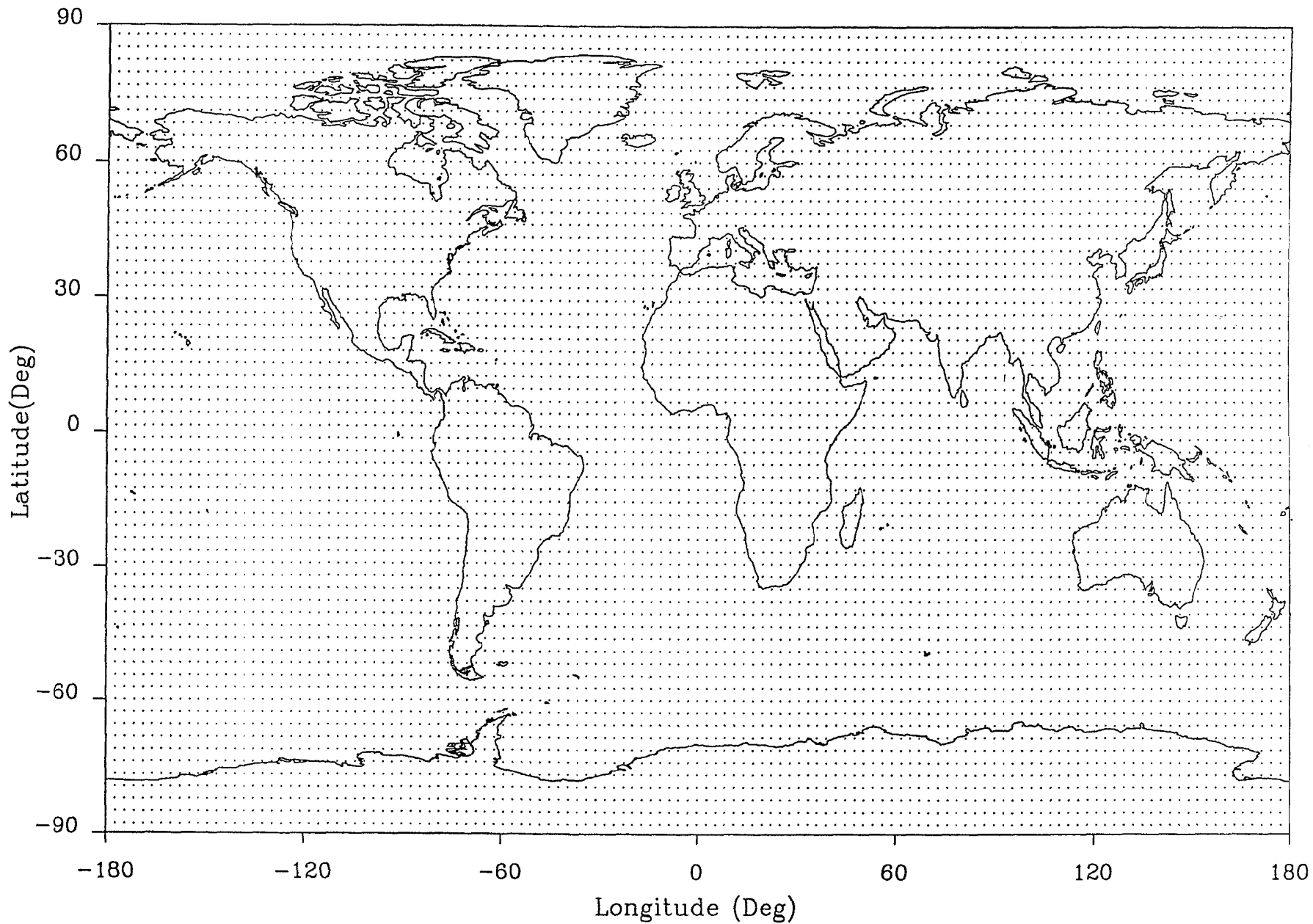


Figure 9

Distribution of transponders at each pressure pevel as a function of latitude and longitude for the uniform initial distribution case.

Figure 10



Distribution of transponders at the 775 mb pressure level after 35 days as a function of latitude and longitude for the initial distribution case

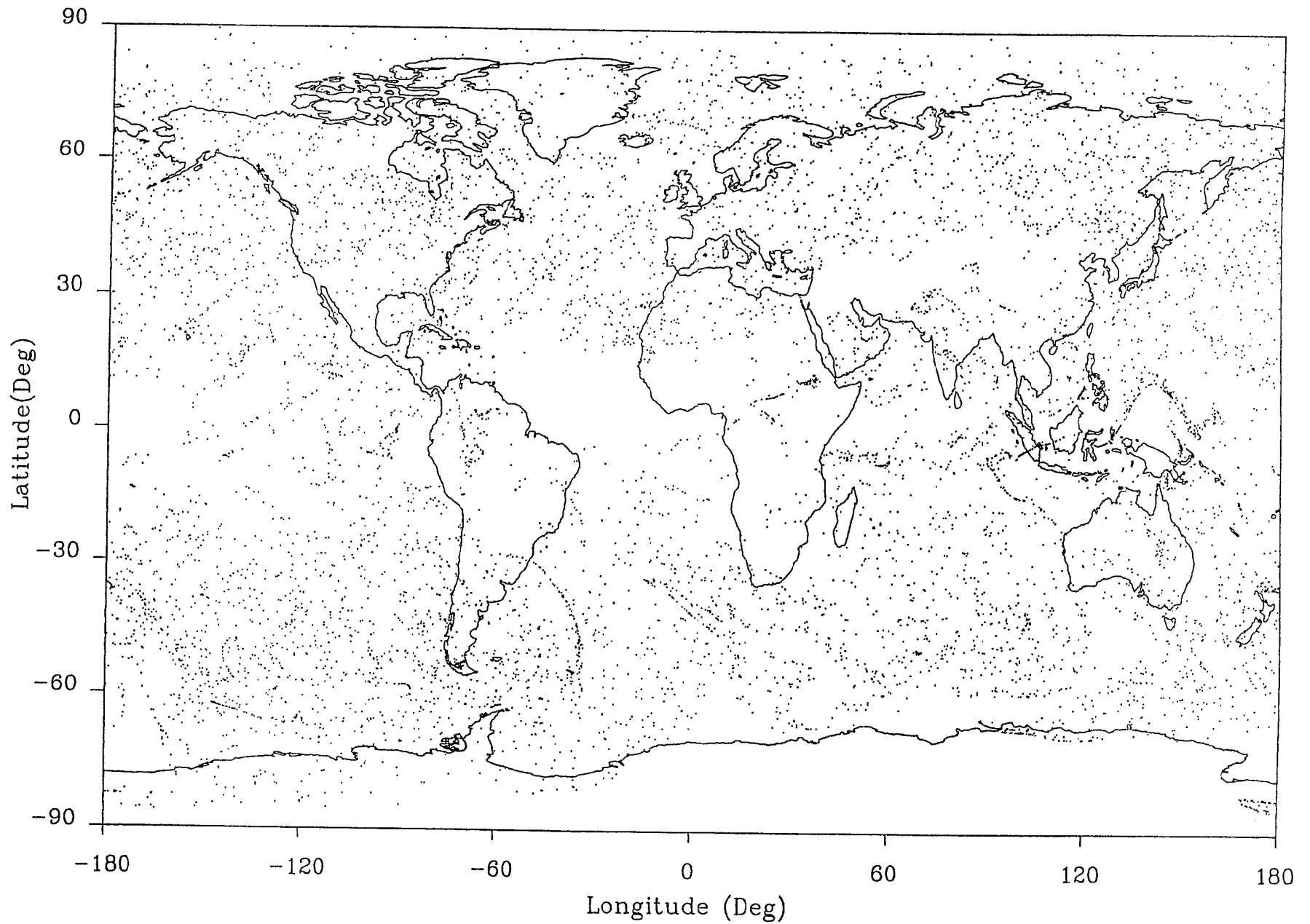


Figure 11

Distribution of transponders at the 200 mb pressure level after 35 days as a function of latitude and longitude for the initial distribution case

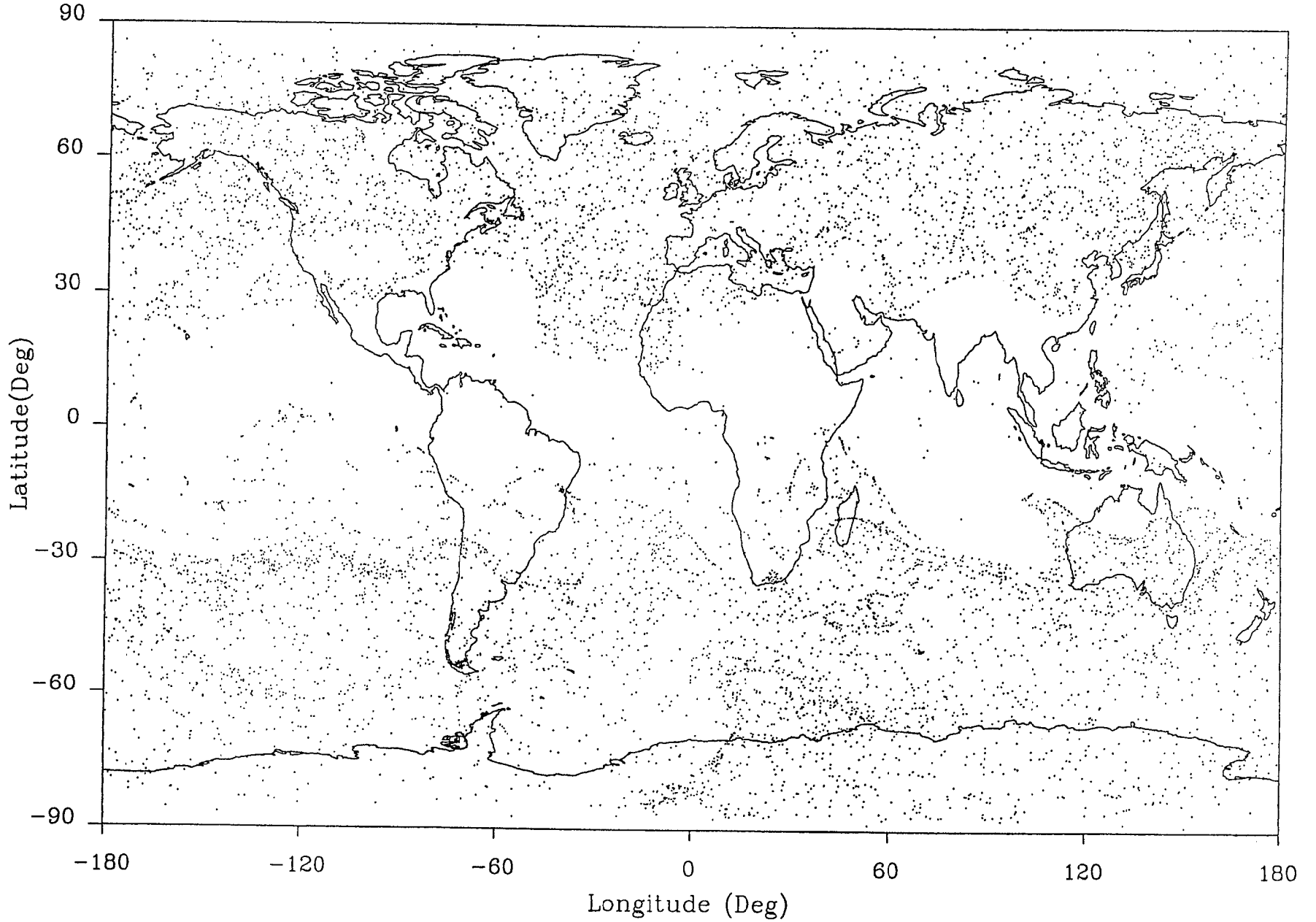


Figure 12

Latitude-longitude map of transponder release sites for the vertical line source
release study

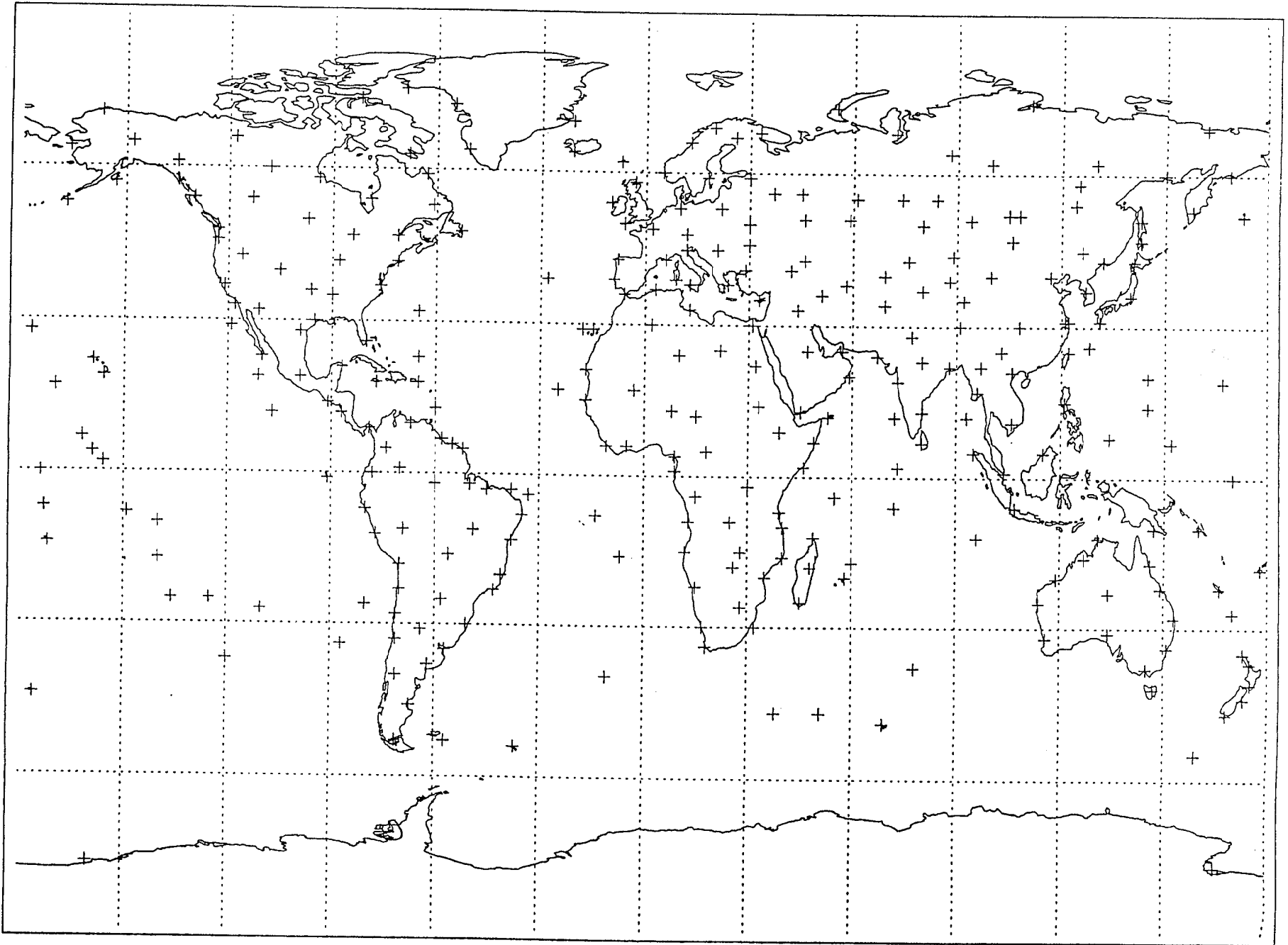


Figure 13

Distribution of transponders at the 775 mb pressure level after 35 days as a function of latitude and longitude for the vertical line source release study

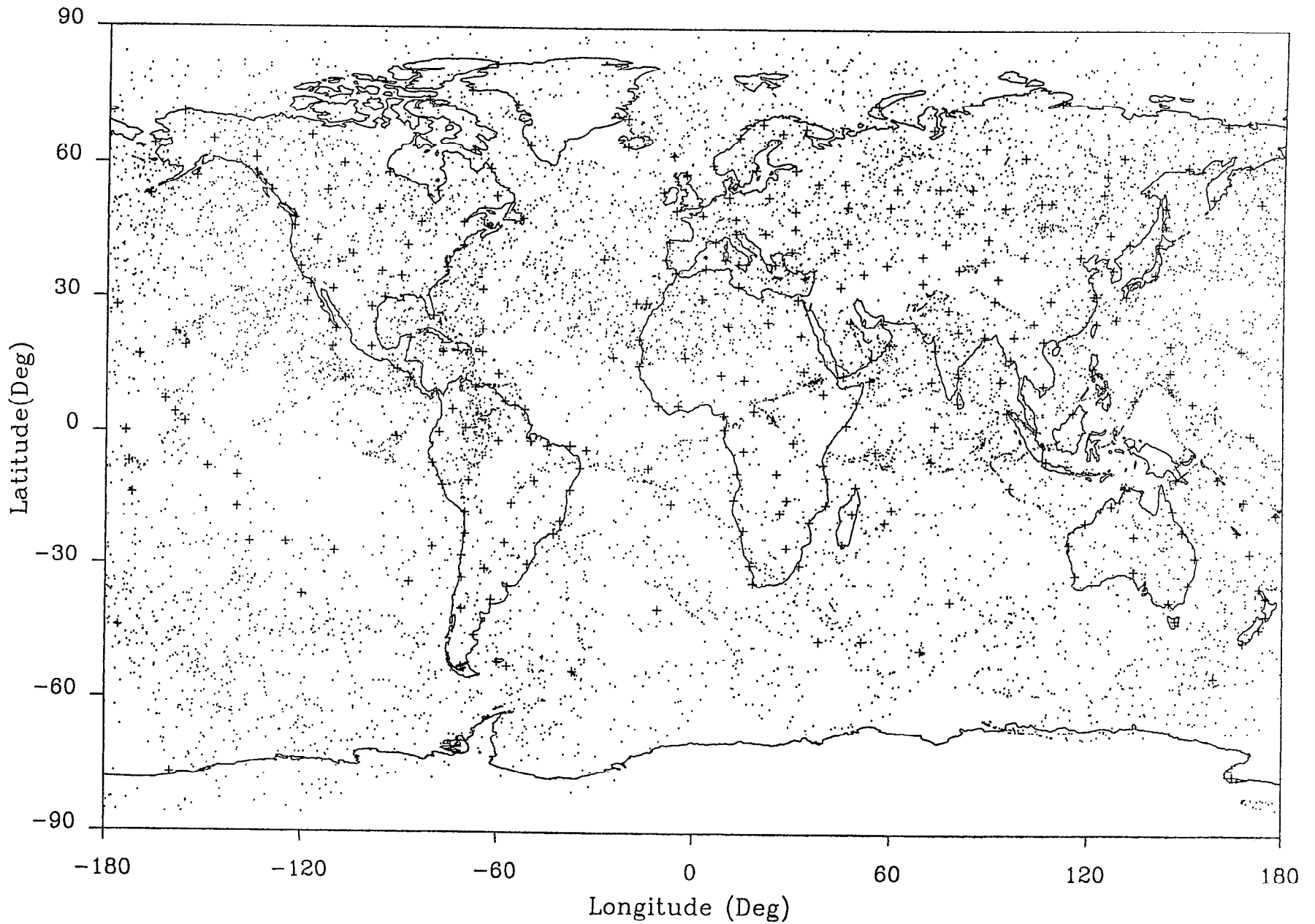


Figure 14

Distribution of transponders at the 200 mg pressure level after 35 days as a function of latitude and longitude for the vertical line source release study

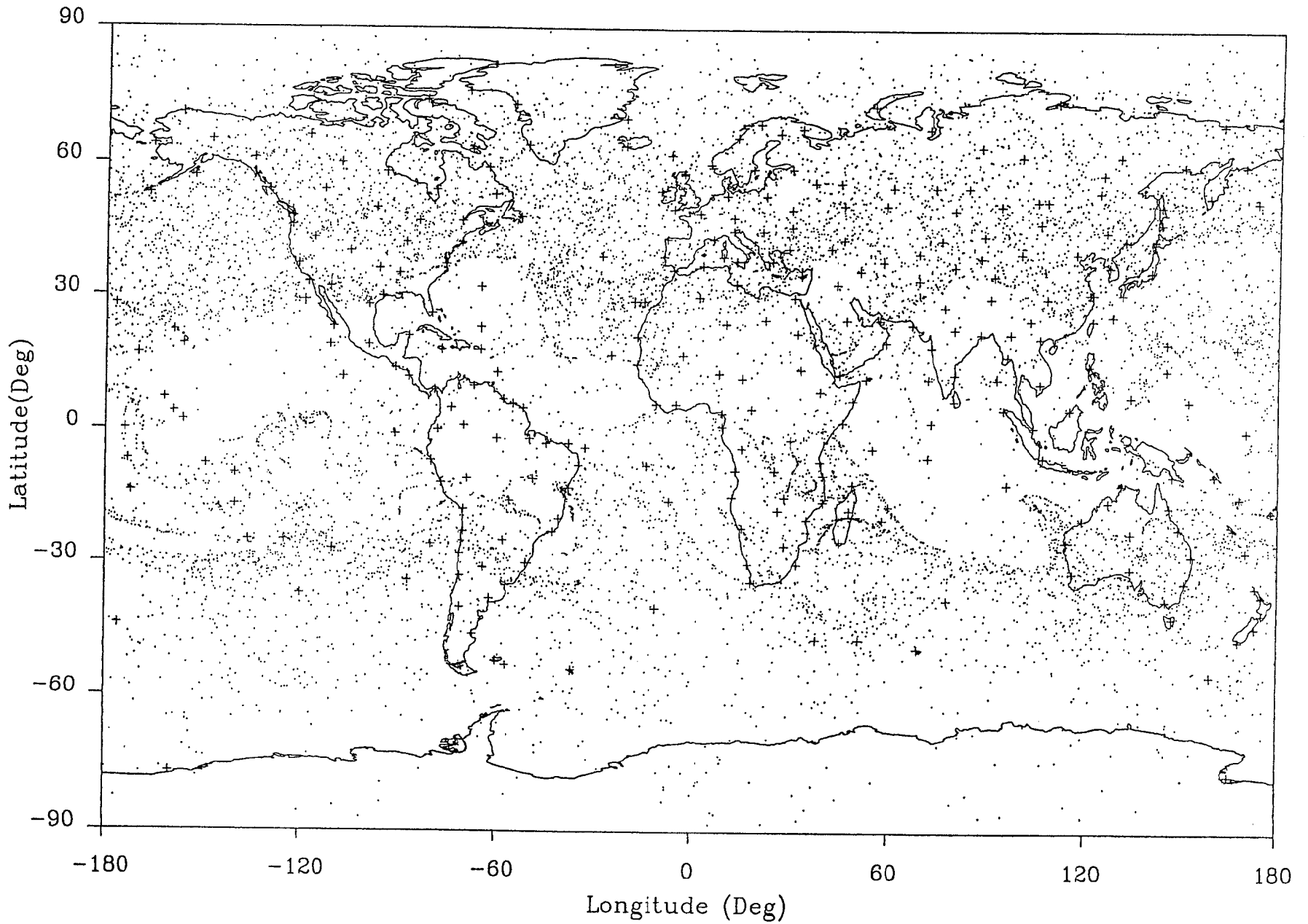


Figure 15

Polar view of the calculated trajectory of a transponder released at the 200 mb pressure level from Christchurch New Zealand

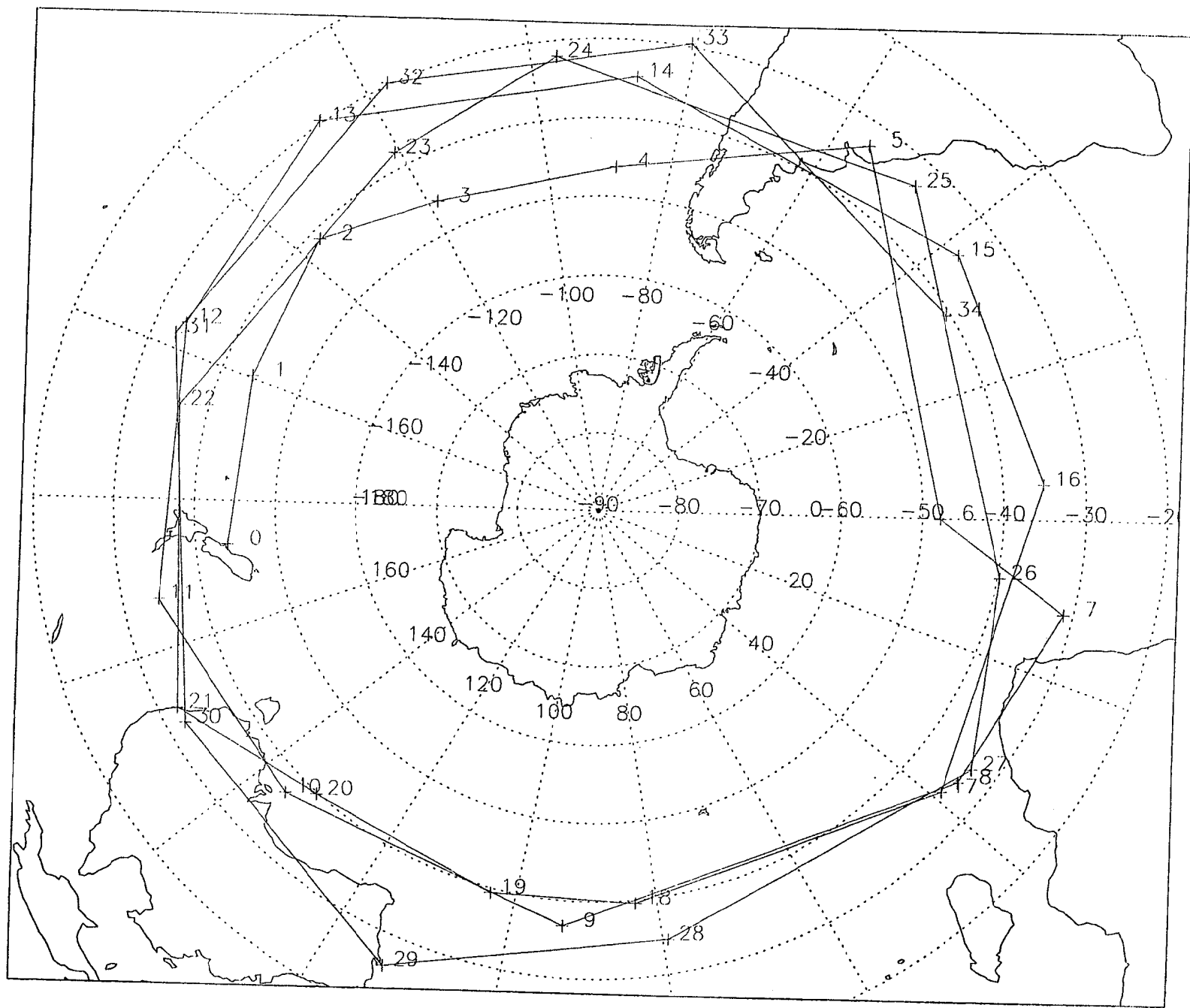


Figure 16