New Zealand After Nuclear War

THE BACKGROUND PAPERS

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BACKGROUND PAPER 2

POSSIBLE IMPACTS ON NEW ZEALAND CLIMATE AND GROWING SEASON

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This is one of a set of background papers prepared, in consultation with the Nuclear Impacts Study Team, from material provided by a wide range of contributors for a study of the impacts on New Zealand of a major nuclear war. Along with other sources, the papers comprised the basis of the book ***New Zealand After Nuclear War****, by Wren Green, Tony Cairns and Judith Wright, published by the New Zealand Planning Council, 1987. The assumptions that the study was based on are explained in Background Paper 1, note particularly the assumption that New Zealand is not a target, and the variable assumption involving an electromagnetic pulse (EMP - for an explanation, see Background Paper 5).*

BACKGROUND

The suggestion that a Northern Hemisphere nuclear war might initiate serious global climatic changes was first made by Crutzen and Birks (1982), who calculated that sufficient smoke could be produced by burning cities and forests to reduce substantially the amount of sunlight reaching the surface of the earth. A preliminary estimate of the climate response to high smoke concentrations was made by Turco *et al.* (1983), using a simplified model which calculated the temperature profile of the atmosphere for various concentrations of smoke and dust. They estimated surface temperature reductions of 30-40°C over Northern Hemisphere continents (and 2-3°C using parameters appropriate to an ocean surface) for a range of war scenarios, and confirmed that a critical factor was the amount of sooty smoke produced in the fires ignited by the nuclear detonations. Dust thrown into the atmosphere by surface bursts was relatively unimportant, because soot was about 100 times more effective than dust at absorbing solar energy. Since cities contain such large stores of combustible materials, even a "limited" war of 100 megatons (MT) could trigger climatic effects almost the same as a more widespread 5000-MT war, if major urban centres were targeted.

The simple model of Turco *et al.* was soon followed by more sophisticated studies, using three-dimensional general circulation models* (GCMs). These accounted for regional and seasonal variations and explicitly calculated the large-scale winds and their horizontal transport of heat. The simulation by Covey *et al.* (1984) of a July war predicted that Northern Hemisphere land areas underlying the smoke would cool by about 15°C, although natural weather variability produced an initial patchiness in the distribution of sub-freezing sites. Absorption of sunlight by the smoke layer resulted in very high temperatures (up to 80°C above normal) in the upper troposphere* near 10 km, which

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*Terms marked by an asterisk are defined in the appended glossary.

modified the normal circulation. Cloud formation and rain was suppressed, and a cross-equatorial flow at the height of the smoke layer was initiated (Fig. 1). Covey *et al.* kept the smoke fixed at its original location of 30-70^{o}N. However, the model prediction of a new cross-equatorial flow suggested that the changed circulation would transport smoke across the equator, and so affect Southern Hemisphere countries within a few weeks of a nuclear war in the Northern Hemisphere.

Some of the restrictive assumptions made by Covey *et al.* such as holding the location of the smoke fixed and not accounting for rainout*, were removed in subsequent studies. Haberle *et al.* (1985) allowed for smoke to be transported by the atmospheric winds, and showed that interhemispheric exchange would indeed be a problem. An important qualification to this result was that there was a strong seasonal dependence in the intensity of cross-equatorial transport. Smoke was driven southwards by strong solar heating of the smoke, and this occurred in the Northern summer and spring (and presumably autumn too, although this simulation was not done). For a war fought in the Northern winter (January), the smoke remained near its original latitudes. Malone *et al.* (1986) estimated the rate at which smoke would be washed out from the atmosphere, using the model's own calculation of precipitation. They found the residence time of the smoke in the atmosphere was greatly increased by the reduced rainfall in the stabilised troposphere, and the lofting of the heated smoke into the stratosphere*.

The Scientific Committee on Problems of the Environment - *Environmental Consequences of Nuclear War* (SCOPE-ENUWAR Report Vol. 1: Pittock *et al.*, 1986; Vol. 2: Harwell and Hutchinson, 1985) documented these findings, along with a great deal of other work on the physical and biological effects of a major nuclear war. There has been criticism of the SCOPE report in some quarters, but a lot of this seems to be politically motivated. A SCOPE meeting in Bangkok (February 1987) agreed that the original findings need not be fundamentally modified. Since the report was published, better estimates have been made of the amount of combustible material in industrialised countries, although there is still considerable uncertainty about how much might actually burn in a nuclear war (Penner, 1986). Recent calculations suggest that less soot might be scavenged in the smoke plume in the first few days than previously assumed (now 10-30% removal, rather than the 25-50% of earlier assumptions). Laboratory and theoretical studies on aging soot particles indicate that aggregation in the smoke cloud does not greatly alter the absorption of solar radiation. Pittock and Garratt (1987) and Ghan *et al.* (1987) have looked more carefully at the modelling of the surface atmospheric layer (the boundary layer*), and suggest there may be greater surface cooling in the early weeks than the general circulation models indicate.

LIKELY IMPACTS ON NEW ZEALAND CLIMATE

Model predictions of Southern Hemisphere climate changes

One of the major uncertainties in the nuclear winter* studies is the estimation of climate changes in the Southern Hemisphere. Most GCM simulations have not been extended beyond about 40 days from war onset, so there has not been time for the Southern Hemisphere circulation to adjust fully to the changed conditions. However, some predictions about Southern Hemisphere effects can still be made. In Fig. 2 (from Malone *et al.*, 1986) we see sufficient smoke has penetrated into the southern stratosphere by day 40 of a July war to reduce levels of sunlight at the ground by 10-20% in southern middle latitudes. Malone *et al.* predicted temperature reductions in Australia of 5-10°C during the third week of the simulation as the smoke veil spread overhead, but these were short-lived and were reduced to a few degrees below normal by the end of the fourth week (presumably because of the ameliorating effect of the southern oceans and the rapid adjustment of the winter circulation that compensated for the reduction in sunlight). No temperature changes were reported for New Zealand, because the model resolution* was too coarse to distinguish the New Zealand land area from the surrounding ocean.

The SCOPE report differentiated effects on climate and agriculture according to the time elapsed after smoke injection - the so-called "acute" and "chronic" phases. The acute phase applied only to the first few weeks before there was any impact on New Zealand. Therefore, our comments apply to the chronic phase, which would begin about a month after a Northern Hemisphere war and might last for 6 months or longer. Sea surface temperatures are expected to fall only slowly, owing to the large heat capacity of the upper-ocean layer. New Zealand is a relatively small land mass surrounded by ocean, so would not experience temperatures drops as large as continental Australia, at least on windward coasts. Rainfall patterns might be disrupted with the most likely result (inferred from Fig. 1) being reduced rainfall in the northern parts of New Zealand in winter, if the war were to occur in the Northern Hemisphere spring or summer.

Dr Robert Malone of the Los Alamos National Laboratory extended his nuclear winter model calculations out to 80 days, to estimate the smoke amounts likely to ultimately reach the latitudes of Australia and New Zealand (Pittock, pers. comm.). This resulted in "absorption optical depths" of about 0.2 to 0.3, i.e. absorbing approximately 20-30% of sunlight in a vertical path through the smoke layer. (Absorption would be even greater if the sun was not directly overhead.) This amount of smoke is relatively modest compared to Northern Hemisphere levels during the acute phase, and Pittock and Garratt (1987) argue that to simulate surface temperature effects under these conditions a model should include the diurnal cycle of solar radiation, a stability-dependent boundary layer*, and also take into account the heat capacity of the soil.

Pittock and Garratt found quite significant surface cooling could occur for a smoke optical depth of 0.2. For example, in winter at 45°S (or the latitude of Oamaru, say), they calculated a sharp drop of 3°C in daily maximum temperature on day "zero" when the smoke layer was first introduced, followed by a progressive reduction in daily minimum and maximum surface air temperature of between 0.4 and 0.6°C per day for the 15 days of the model experiment; i.e., a total drop of about 12°C in the maximum, and 6°C in the minimum. Surface cooling was also found to be more pronounced in winter than in summer (due to a longer slant path for the solar beam through the smoke), which is especially significant since the (Southern Hemisphere) winter is the season when smoke from a Northern nuclear war is expected to move rapidly across the equator. While Pittock and Garratt's results are still preliminary and do not allow for the ameliorating effect of a nearby ocean, the rapid cooling is indicative of what could happen in New Zealand under light-wind conditions. Further research on this possibility is needed.

Frost occurrence

The occurrence of frosts can affect agricultural productivity significantly, since brief episodes of chilling or freezing temperatures during the growing season will kill many crops. Table 1 (tables and figures follow at the end of this paper) lists economically-important crops grown in New Zealand that are frost-sensitive. All the productivity from these crops would be a risk if exposed to even a short period of freezing temperatures during the growing season.

An estimate of how the length of the frost-free period in New Zealand varies with temperature has been made by S. Goulter (pers. comm.) by statistical regression of frost-free period against mean annual temperature for a number of sites around the country. Results varied considerably between sites, but on average the length of the frost-free season reduced by about 41 days per $1^{o}C$ drop in mean annual temperature for North Island stations, and by about 28 days for South Island stations. However, this regression applies under conditions of a normal diurnal and annual cycle, and these may be quite different for the mild nuclear "winter" conditions we might experience in New Zealand. Models suggest that a smoke veil will not only reduce the daily maximum and minimum temperatures, but also dampen the diurnal cycle of temperature; i.e., the maximum temperature will be reduced more than the minimum (MacCracken and Walton, 1984; Pittock and Garrett, 1987). Furthermore, the SCOPE report estimated the sensitivity of the frost-free season to be about 10 days per degree C. This value, albeit for continental U.S. stations, is much lower than those found by Goulter for New Zealand, so we developed an alternative approach to estimating the variation of frost-free period with temperature.

In our frost-occurrence model, the daily minimum temperature was divided into two components: a long-term mean that varied smoothly with day of year (T_{min}), and a random component of zero mean and specified standard deviation (T_{ran}). Observations of minimum temperature and statistics of frost occurrence (New Zealand Meteorological Service, 1977, 1981) were used to calibrate the model as follows. For a given site, a daily minimum temperature series was simulated using the observed long-term daily mean minimum temperature (actually interpolated from the monthly means) and a trial value for the daily temperature standard deviation. The mean length of the frost-free period was then calculated. This procedure was repeated with different trial values for the daily temperature standard deviation (or amplitude of the random forcing), until the calculated mean frost-free length matched the observed value. This model of daily temperature was a very simple one and, in particular, no allowance was made for day-to-day persistence in temperatures. Nevertheless, frost statistics such as percentiles of frost-free period and the expected number of frosts per month were reproduced reasonably well for most of the stations tested.

A series of Monte Carlo* simulations was then done with small perturbations to the annual cycle of daily minimum temperature (T_{min}) and the best-fit daily standard deviation (T_{ran}). The imposed perturbations were held constant throughout the year. The sensitivity of the frost-free period to changes in the temperature distribution could then be estimated from the model. Just how sensitive the frost-free period is to changes in T_{min} (shown in Fig. 3, in units of days/^{o}C) depends on the "nature" of the site, which we have characterised in terms of the annual mean minimum temperature and the annual range in the minimum. Cold sites with a large annual range in the minimum temperature (i.e., more continental climates, such as occur in Central Otago) show a change in frost-free period of about 15-25 days per degree change in minimum temperature. Warmer sites with a small annual temperature range show a much larger sensitivity. For example, the frost-free period at Ophir in Central Otago (currently 93 days) decreases by about 24 days for every $1^{o}C$ drop in minimum temperature, while the frost-free period at Tauranga (currently about 350 days, so that some years experience no frosts) decreases by over 50 days for a $1^{o}C$ temperature drop.

The results of Fig. 3, which apply for no change in temperature variance from present conditions, support the findings of S. Goulter (New Zealand Meteorological Service) that New Zealand is more susceptible to increased frost occurrence for small temperature drops than continental U.S. sites. However, an additional result from this Monte Carlo approach which was not previously considered in the SCOPE work (Harwell and Hutchinson, 1985, p. 274 ff) is the change in frost occurrence with a change in the temperature variance. The issue of how temperature variance in the post-nuclear war environment would differ from present conditions has not been satisfactorily resolved by the numerical models. Daily temperature variance may increase at surface sites near the periphery of the smoke cloud, where horizontal temperature gradients will be enhanced (Pittock *et al.*, 1986). On the other hand, Pittock and Garratt (1987) have shown a weaker diurnal temperature cycle under a thin uniform smoke cloud (the more likely scenario for New Zealand), and this probably also implies a smaller day-to-day variability. Our simulation study showed that the length of the frost-free period (F) was twice as sensitive to changes in the random forcing (T_{ran}) as to changes in the minimum temperature (T_{min}), with a correlation coefficient between the two sensitivities of -0.98 for the 31 sites tested. That is, the length of the frost-free period decreases for a drop in the minimum temperature, but increases for a drop in the temperature variance. Thus, we have the following approximate relation for calculating changes (Δ) in frost-free period as a result of changes in the mean level of minimum temperature and its day-to-day variability:

$$\Delta F = S (\Delta T_{min} - 2 \Delta T_{ran}),$$

where S is the sensitivity of F per degree drop in minimum temperature, and can be read off Fig. 3.

The actual change in frost-free season after a nuclear war thus depends on the combination of two factors: the change in minimum temperature, and the change in daily temperature variability. As an example of how this combination of factors operates, let us consider a scenario for Ophir (where S = 24) where the minimum temperature drops by 1°C: with no concurrent change in temperature variance, the frost-free period would decrease by about 24 days; if the standard deviation of the daily minima also decreased simultaneously by 0.5°C, the length of the frost-free season would be unchanged from present conditions; if T_{ran} decreased by more than 0.5°C, the length of the frost-free season would actually increase (as a result of fewer frosts in early autumn or late spring).

LIKELY IMPACTS ON NEW ZEALAND AGRICULTURE

Controlling climatic factors

Plant growth* and development* can be affected by changes in sunlight levels, rainfall, and temperature. Growth, which is the accumulation of dry matter by photosynthesis, is controlled largely by light radiation (Wilson and Jamieson, 1985) and the supply of carbon dioxide and water, with the exception of grass growth where temperature is an important factor. Light reductions of 10-20% might be expected in New Zealand latitudes (Malone *et al.*, 1986) for up to several months, but no work has yet been done on the response of New Zealand agriculture to these conditions. Model predictions of rainfall changes are still very uncertain, and no impact studies have been done here either. J. Baars and M. Rollo of the Ruakura Soil and Plant Research Station have considered the effect of temperature reductions on grass growth, and their findings are considered in section 3.3.

Plant development, which is the progress a plant makes from seed germination to maturity, is determined mainly by temperature (Monteith, 1981). For crops in temperate climatic zones, the higher the temperature the faster a plant will develop towards maturity. Optimum crop yields require sufficient solar energy integrated over a period of time: a convenient measure of the cumulative amount of heat available for crop maturation is given by a temperature summation known as thermal time* (Monteith, 1981). The summation is carried out only for days when the mean temperature exceeds some base temperature* (different for different crops), below which development cannot occur. For particular crop species and varieties the thermal time requirements are relatively constant, and if not satisfied by the end of a growing season*, the crop will not mature. Base temperatures and thermal time requirements for some of the crops grown in New Zealand are shown in Table 2. Salinger (1986) calculated the effects of various temperature changes on New Zealand crop production, and in the following section we summarise the results for two of his temperature reduction scenarios.

Effect on horticulture and cropping

The effects of two temperature reductions are examined: scenario 1, where temperatures are reduced by 1^{o}C for twelve months; and scenario 2, where temperatures are reduced by 3^{o}C for three months and 1^{o}C for a further nine months. Salinger (1986) showed that the impact of a given temperature reduction depended on the time of year at which the cooling started, and also on the latitude of the site. If the cooling of scenario 1 began in the New Zealand autumn or winter (between March and June), a crop requiring 1,000 thermal time units (TT) would mature with a delay of 12-40 days at Ruakura (latitude 37^{o} 47'S). However, if the same cooling pattern began in spring or summer, the thermal time accumulations would be reduced to such an extent that a 1,000 TT crop would not reach maturity at all. Crops at more southerly sites would be affected more severely because of the lower mean temperature and therefore lower thermal time accumulation under normal conditions. Crops requiring less heat and subject to the same cooling pattern would be less affected, and conversely crops needing more than 1,000 TT to mature would be more susceptible.

Increases in crop maturation time are shown in Table 3 at sample sites of Ruakura and Ashburton for the two temperature reduction scenarios, where scenario 2 is the worst of the four possible cases (with the cooling starting in spring). At present, cereal and horticultural crops requiring higher thermal time, such as kiwifruit and some citrus, can be successfully matured as far south as the Nelson and Blenheim areas. Field tomatoes will mature in Canterbury. Under scenario 2 however, kiwifruit and citrus would have difficulty in maturing in all localities apart from the Kerikeri, Bay of Plenty and Gisborne districts, while tomatoes would be confined to North Island horticultural areas. Crops which require less heat for maturation (including other horticultural crops and cereals such as maize, wheat and barley) would be harvested three to five weeks late, except in southern New Zealand where even these crops may not mature at all.

Under scenario 1 (less severe), most horticultural and cereal crops would mature some two to three weeks late. In areas where these crops are near the limit of their climatic range, such as grapes in Marlborough and some subtropical crops in Waikato and Hawke's Bay, the current year's crop would not mature at all. To put these figures in perspective, normal interannual temperature variations can alter the growing season by up to plus or minus 1-2 weeks about the average value. Comparing recent production with that of 1982/83 (the year of an extreme El Nino event), Newton (pers. comm.) notes a 20% decline in North Island maize yields for the 1982/83 summer when temperatures were 1-2°C below average.

Effect on pastoral production

As pasture is continuously grazed, it has no specific thermal time requirements. However, Baars (1980) has measured the base temperature as 5.5°C, meaning that pasture growth ceases below this temperature. Baars and Rollo (pers. comm.) have modelled the effect of various temperature reductions on pastoral production in Waikato, Canterbury and Southland. Their results are presented (Figs. 4, 5; Table 4A) for a temperature reduction scenario of a 3°C drop in spring, followed by a 2°C drop in summer and 1°C for the next 18 months. The effect on rate of grass growth is shown in Figs. 4 and 5. In Table 4A these results have been converted into the accumulated change in total dry matter production.

Annual pasture production declines to 81% of normal in the Waikato and 64% of normal in Southland for the first year, and with a 1°C temperature reduction in the second year to 89% and 83% respectively. More dramatic is the effect of a 3°C reduction in the first spring: production ranges from 66% of normal in the Waikato to 34% of normal in Southland. These figures demonstrate the sensitivity of pasture production to comparatively small temperature reductions, and also show a dependence on the season at which cooling commences. The sensitivity of pasture production to greater reductions in mean temperature during the spring season are shown in Table 4B. For the range of temperatures considered, there is approximately a linear decline in production with temperature, the decline being greater at higher latitudes.

Another pasture production model (Newton, pers. comm.) yields similar results on an annual basis, but gives higher pasture growth rates for cooling in the first summer because of lower evapotranspiration rates.

UNCERTAINTIES REMAINING AND SUGGESTED RESEARCH

There are a number of steps required in the numerical modelling of climatic effects due to a large-scale nuclear war, and at each stage some simplifying assumptions are usually necessary. International research continues on aspects of the targeting scenario, fuel loading, smoke production and properties, plume dispersal, climate modelling, and atmospheric chemistry and radioactivity, along with studies of the impact on agricultural and human systems. The SCOPE report (Pittock *et al.* 1986, Chapter 8; Harwell and Hutchinson, 1985, Appendix B) lists research topics which are still relevant today. We concentrate here on topics that have some application to New Zealand.

1. Longer GCM simulations: extending the general circulation model simulations to cover a period of a year or more is desirable, to indicate the range of climatic possibilities in the Southern Hemisphere. At the beginning of 1987, Malone (pers. comm.) and his group at the Los Alamos National Laboratory, USA, made a seven-month simulation of the climatic effects from a nuclear war starting in July. They found significant amounts of smoke remained in the Southern Hemisphere stratosphere at the end of seven months, and plan to make further experiments. Smoke residence times of six months or more would

inevitably lead to some cooling of the ocean surface.

Unfortunately, a serious limitation with current GCMs is the lack of a fully-interactive ocean: all the models (including the Los Alamos one) hold ocean temperatures fixed at climatological values over the period of the experiment. This shortcoming is unlikely to be overcome in the near future, so predictions of temperature changes over small land areas in oceanic regions like the South Pacific will continue to be imprecise.

2. Investigate further the sensitivity of the results to the season of smoke injection into the atmosphere. In particular, many published studies consider the effects of January and July wars, and occasionally a March-April war, but the September-October period has been largely neglected (because of its similarity to March-April in terms of solar radiation levels). At this latter time of year, there may be sufficient solar heating in the north to drive smoke across the equator, and local studies have shown New Zealand agriculture to be especially susceptible to temperature perturbations in the spring season.

3. Modelling of the ocean surface layer, and examining how water surface temperatures respond to a smoke veil, is needed to supplement the deficiency of the GCMs.

4. Effects of regional volcanic eruptions: past data on climatic effects of volcanic eruptions have been considered inappropriate for comparison with full nuclear winter conditions (because volcanic dust is much less absorbing of sunlight than sooty smoke). In the Southern Hemisphere, however, where climatic consequences are less severe, the volcanic eruption data may be more relevant.

5. Investigation of sea-breeze circulations in the nuclear winter context is needed. Although a smoke layer will cause some reduction in land surface temperature, the increased temperature gradients between land and sea will set up a local circulation (the "sea breeze") that may limit the amount of cooling possible over small land masses. The resolution of general circulation models is too coarse to determine this effect for New Zealand.

6. The effects of rainfall and light reduction on plant growth in New Zealand need to be estimated; so far, only temperature effects have been considered in any detail.

7. Further sensitivity studies on temperature extremes are needed. A knowledge of how lower temperatures and sunshine or cloudiness variations affect high and low temperature extremes (including frost occurrence) is extremely important in the South Pacific, where crops are very sensitive to small deviations from the usual temperatures (Harwell and Hutchinson, 1985).

CONCLUSIONS

In this paper, we have restricted ourselves to considering the delayed climatic effects from a nuclear war. In the event of a war, the direct effects of the nuclear detonations (heat, blast, radiation) are expected to be confined mainly to the Northern Hemisphere (see Background Paper 9). Even with accelerated cross-equatorial transport of global fallout by the smoke clouds, radiological doses in the Southern Hemisphere would be relatively insignificant, and local fallout would only be important within a few hundred kilometers downwind of any surface burst. New Zealand would suffer from a loss of communications and essential technology (Background Papers 5, 6, 7 and 8) and, as considered in this paper, from possible climatic changes that would impact on our agricultural production.

Southern Hemisphere climatic effects have been shown to be seasonally dependent, a thin veil of smoke reaching southern mid-latitudes within a few weeks if the war was conducted in Northern Hemisphere spring or summer. For a war during Northern Hemisphere winter (January), probably no smoke would reach Southern Hemisphere mid-latitudes for 6 months and then in much reduced amounts. Any local contingency planning directed towards minimising our agricultural losses should take account of this seasonal variation. For a January war, we might adopt a cautious "wait and see" approach. For a July war, prompt advice would need to be given to the farming community about the best cultivars to plant in the coming spring to withstand the expected lower temperatures.

Reductions in average temperature extend the time required for crop maturation. The impact of a given temperature depression depends on its commencement date as well as its magnitude and duration. Short-term cooling at the peak of the growing season (spring and summer) would be most serious; cooling in the dormant season (winter) would be less significant to many crops. However, as pointed out from the circulation model studies, a scenario where the greatest temperature drop occurred in summer would be the least likely, since smoke from the Northern Hemisphere would not be driven rapidly south in a northern winter war.

Smoke would reach the Southern Hemisphere in greatest quantities following a northern spring or summer war when much of New Zealand agriculture would be in a dormant period. If sufficient smoke remained in the stratosphere until the subsequent growing season, then again there would be adverse climatic consequences. There is, however, considerable uncertainty in how long smoke would remain in the stratosphere, and also in the magnitude of temperature changes at the surface. The various scenarios considered above attempt to cover a reasonable range of possibilities. A 1°C drop during the cool season (May to October) would have little effect on most agricultural activities. A twelve-month depression of average temperature by 1°C would reduce the length of the growing season by two to three weeks and crops grown at their climatic limits would fail to mature. If average temperatures were to drop by 3°C in the spring, this would reduce pasture production, especially in the hill country, cause failure of many warm-temperate crops, and delay harvest of hardier species by about three to five weeks with associated lower yields. Any impact would be greater in the south of New Zealand.

An increase in the frequency of frosts could affect a large number of economically important crops. North Island sites are the most sensitive to any temperature changes, and inland Central Otago sites the least sensitive. Throughout the North Island the length of the frost free period would decrease by at least 30 days for every 1°C drop in average minimum temperature. However, a concurrent change in the day-to-day temperature variability could counteract this tendency for more frosts. Current models do not give us sufficient information to estimate the effect of this second factor.

Even relatively small temperature decreases would reduce New Zealand's primary production significantly. Temperature is the most important climatic element affecting plant development, and there would be additional impacts, although probably of less significance, if other factors such as rainfall and reduced sunlight were considered.

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REFERENCES

Baars, J.A., 1980. "Development of a simulation model for pasture growth". *Proceedings of the Agronomy Society of New Zealand,* 10, 103-106.

Covey, C., Schneider, S.H., and Thompson, S.L., 1984. "Global atmospheric effects of massive smoke injections from a nuclear war: results from general circulation model simulations". *Nature,* 308, 21-25.

Crutzen, P.J. and Birks J.W., 1982. "The atmosphere after nuclear war: Twilight at noon." *Ambio,* 11, 114-125.

Gallagher, J.N., Biscoe, P.V., and Dennis-Jones, R., 1983. "Environmental influences on the development, growth and yield of barley." *Proceedings of the Agronomy Society of New Zealand,* 13, 21-49.

Ghan, S.J., MacCracken, M.C., and Walton J.J., 1987. "The climatic response to large atmospheric smoke injections: Sensitivity studies with a tropospheric general circulation model." Submitted to *Journal of Geophysical Research.*

Haberle, R.M., Ackerman, T.P., Toon, O.B., and Hollingsworth, J.L., 1985. "Global transport of atmospheric smoke following a major nuclear exchange." *Geophysical Research Letters,* 12, 405-408.

Harwell, M.A. and Hutchinson, T.C., 1985. *Environmental consequences of nuclear war.* SCOPE 28. Volume 2. Ecological and Agricultural Effects. Wiley and Sons, New York.

MacCracken, M.C., and Walton, J.J., 1984. "The effects of interactive transport and scavenging of smoke on the calculated temperature change resulting from large amounts of smoke." *Lawrence Livermore National Laboratory Report UCRL-91446.* Livermore, California.

Malone, R.C., Auer, L.H., Glatzmaier, G.A. and Wood, M.C., 1986. "Nuclear winter: Three-dimensional simulations including interactive transport, scavenging, and solar heating of smoke." *Journal of Geophysical Research,* 91, 1039-1053.

Monteith, J.L., 1981. "Climatic variation and the growth of crops." *Quarterly Journal of Royal Meteorological Society,* 107, 749-774.

New Zealand Meteorological Service, 1977. *Temperature frequencies for selected New Zealand stations.* New Zealand Meteorological Service Miscellaneous

Publications, 158.

New Zealand Meteorological Service, 1981. *An air frost chronology for New Zealand*. New Zealand Meteorological Service Miscellaneous Publications, 173.

Newton, S.D., 1987. *Nuclear War Scenario.* A private submission to the New Zealand Planning Council's Nuclear Impact Study by S.D. Newton, Agronomy Department, Massey University.

Penner, J.E., 1986. "Uncertainties in the smoke source term for 'nuclear winter' studies." *Nature,* 324, 222-226.

Pittock, A.B. and Garratt, J.R., 1987. "Sensitivity studies on nuclear winter effects in the Southern Hemisphere with wider implications." Draft, presented at SCOPE-ENUWAR Workshop, Bangkok, February 1987.

Pittock, A.B., Ackerman, T.P., Crutzen, P.J., MacCracken, M.C., Shapiro, C.S., and Turco, R.P., 1986. *Environmental consequences of nuclear war*. SCOPE 28. Volume 1. Physical and Atmospheric Effects. Wiley and Sons, New York.

Salinger, M.J., 1986. "Nuclear winter: impacts on the growing season in New Zealand." *Journal of Royal Society of New Zealand,* 16, 319-333.

Thompson, S.L., 1985. "Global interactive transport simulations of nuclear war smoke." *Nature,* 317, 35-39.

Turco, R.P., Toon, O.B., Ackerman, T.P., Pollack, J.B., and Sagan, C., 1983. Nuclear winter: Global consequences of multiple nuclear explosions. *Science,* 222, 1283-1292.

Turco, R.P., Toon, O.B., Ackerman, T.P., Pollack, J.B., and Sagan, C., 1987. "Climate and smoke: An appraisal of nuclear winter." Draft, presented at SCOPE-ENUWAR Workshop, Bangkok, February 1987.

Wilson, D.R., and Jamieson, P.D., 1985. "Models of growth and water use of wheat in New Zealand." In: W. Day and R.K. Atkin (eds): *Proceedings of NATO advanced research workshop on wheat growth and modelling,* 9-12 April 1984, Bristol.

Table 1: Crops sensitive to frosts during the growing season.

apples	citrus	melons	pumpkin
asparagus	courgettes	nectarines	squash
avocado	cucumbers	peaches	strawberries
beans (green)	eggplants	pears	sweetcorn
blackcurrants	grapes	plums	tomatoes
capsicum	kiwifruit	potatoes	wheat
cherries	kumara		

Table 2: Thermal time (TT) requirements for maturation of some crops grown in New Zealand.

Crop (^{o}C)	Base temp.	Total TT per season
Karamu Wheat	0	2100
Mata Barley	0	1850
Peas	3	900-950
Lettuce	5	750-850
Maize	6	1650
Beans	10	650
Tomatoes (transplants)	10	800
Sweetcorn	10	800-900
Kiwifruit	10	1100

Table 3: Increase in crop maturation time (in days) at Ruakura and Ashburton for crops with different thermal time requirements (in ^{o}C days) for temperature reduction scenarios 1 and 2 (starting in spring).

Thermal time requirements for maturation.	Increase in maturation time (days)			
	Scenario 1		Scenario 2	
	Ruakura	Ashburton	Ruakura	Ashburton
Above 0°C				
2,000 (Wheat, barley)	9	11	20	22
Above 5°C				
800 (Peas, lettuce)	10	13	27	35
1,800 (Maize)	18	24	31	x
Above 10°C				
700 (Beans)	17	31	33	92
1,000 (Kiwifruit)	40	x	x	x

x Crop unable to reach maturity under this regime.

Table 4A: Pasture dry matter (DM) production in kg dry matter/hectare in Waikato, Canterbury and Southland for temperature reductions of 3°C in spring, 2°C in summer and 1°C for the next 18 months.

(4A)	Spring		Summer		Annual	
	DM	% of normal	DM	% of normal	DM	% of normal
Waikato						
1st year	2,840	66	5,957	81	14,411	81
2nd year	3,831	89	6,700	91	15,984	89
Canterbury						
1st year	1,124	46	4,324	77	7,775	71
2nd year	1,952	81	5,021	89	9,382	86
Southland						
1st year	667	34	3,041	69	5,630	64
2nd year	1,493	76	3,828	87	7,286	83

Table 4B: Pasture dry matter production as in (4A), for temperature reductions of 5°C, 4°C and 3°C in spring.

(4B)	5°C		4°C		3°C	
	DM	% of normal	DM	% of normal	DM	% of normal
Waikato	1,793	42	2,273	53	2,840	66
Canterbury	521	22	760	31	1,124	46
Southland	199	10	393	20	667	34

Fig 1: The zonally-averaged north-south atmospheric circulation from the GCM simulation of Covey *et al.* (1984). Arrows indicate the direction of motion. Units: 10^{10}kg/s. Results have been averaged over days 16-20 of the model simulation, and are for April. The top diagram shows the normal undisturbed circulation. The bottom diagram shows the perturbed circulation after a continuous band of smoke was introduced on day 0 over the latitude-height range indicated by the dashed box.

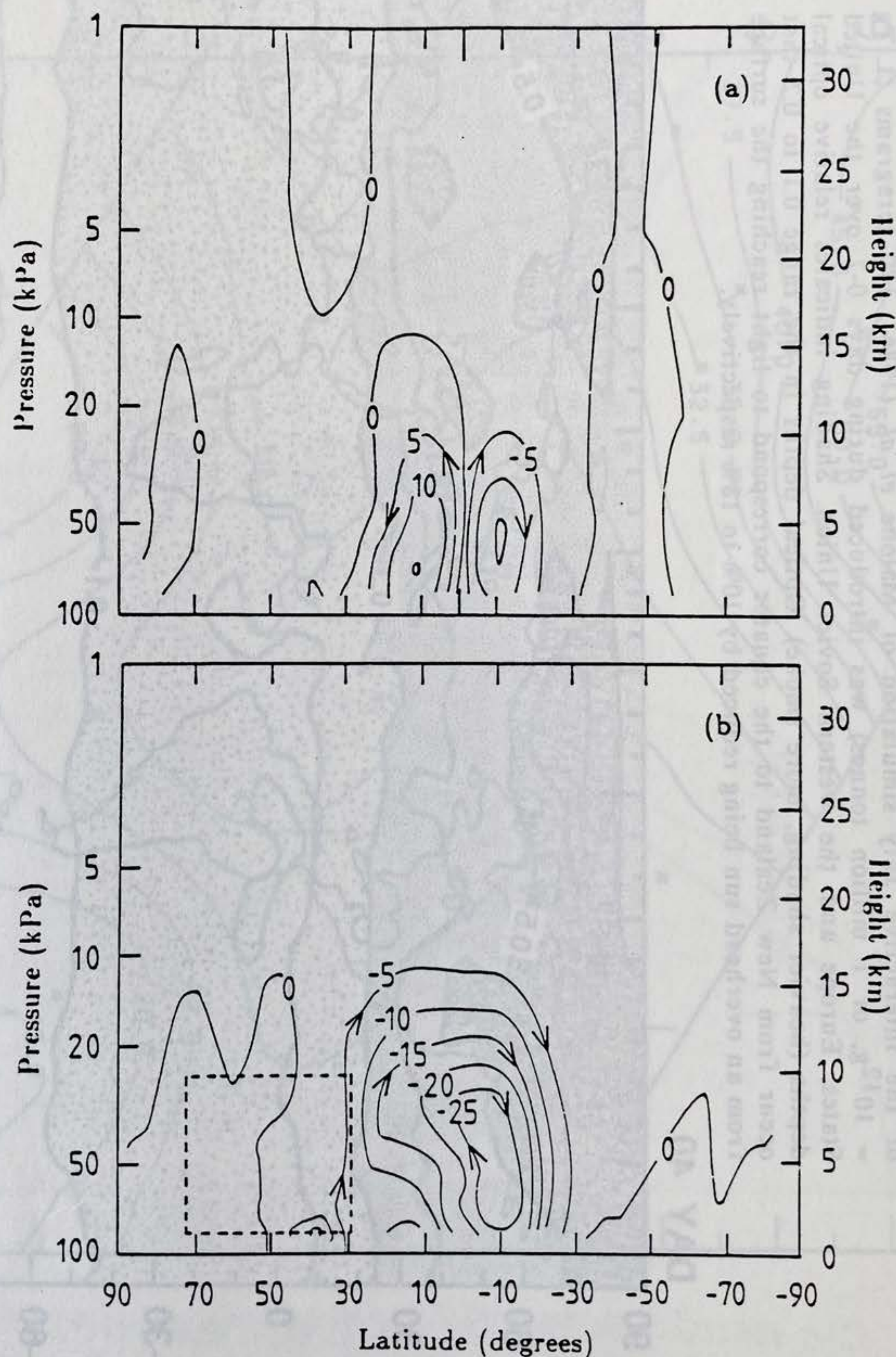


Fig 2: The vertically integrated solar absorption optical depth of smoke at day 40 of the interactive July simulation of Malone *et al.* (1986). 170 teragrams (1 Tg = 10^{12}g, or 1 million tonnes) was introduced during days 0-7 over the United States, Europe and the western Soviet Union. Shading indicates relative optical depths (heavier shading, more smoke). Optical depths in the range 0.1 to 0.2 that occur from New Zealand to the equator correspond to light reaching the surface from an overhead sun being reduced by 10% to 18% respectively.

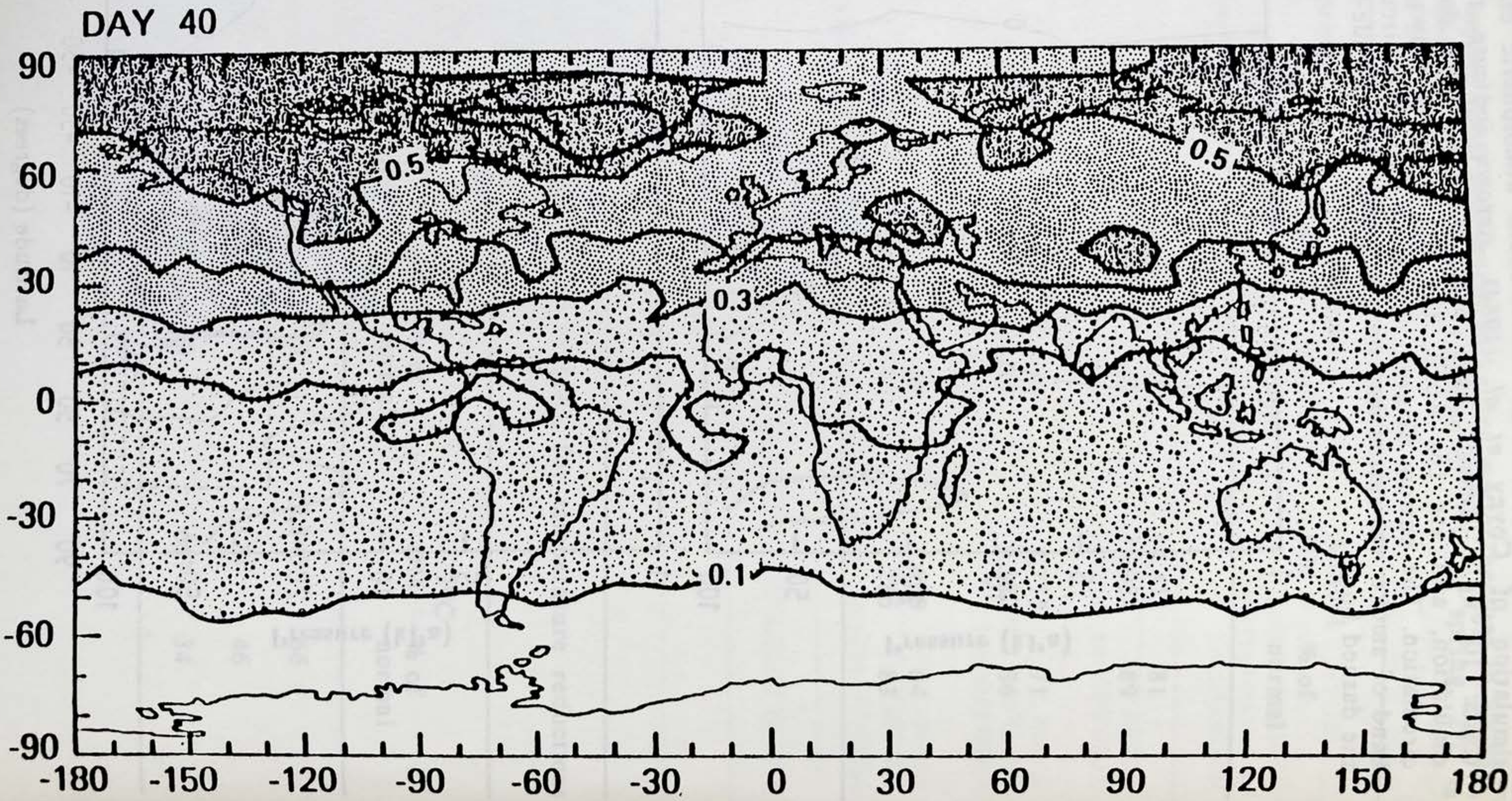


Fig 3: Contour plot of change in length of frost-free period (in days) per degree Celsius change in mean daily minimum temperature. The sensitivity is shown as a function of the annual mean and annual range in the minimum temperature for 31 New Zealand sites (stars indicating location of data points). Contours plotted every 2.5 days per ^{0}C between 20 and 40 days/^{0}C, and every 5 units outside this range.

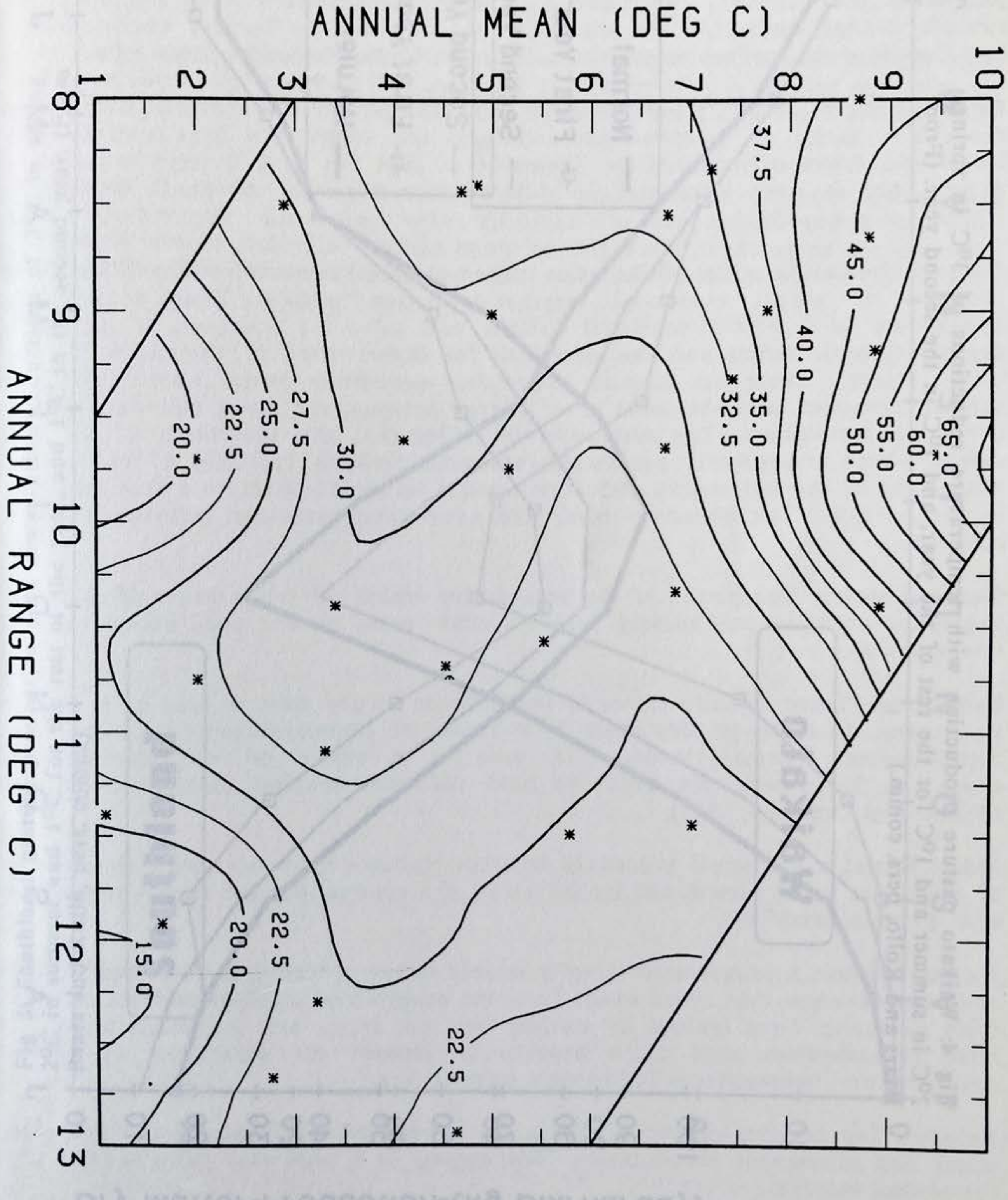


Fig 4: Waikato pasture production with temperature reductions of 3°C in spring, 2°C in summer and 1°C for the rest of the year, and 1°C in the second year. (From Baars and Rollo, pers. comm.)

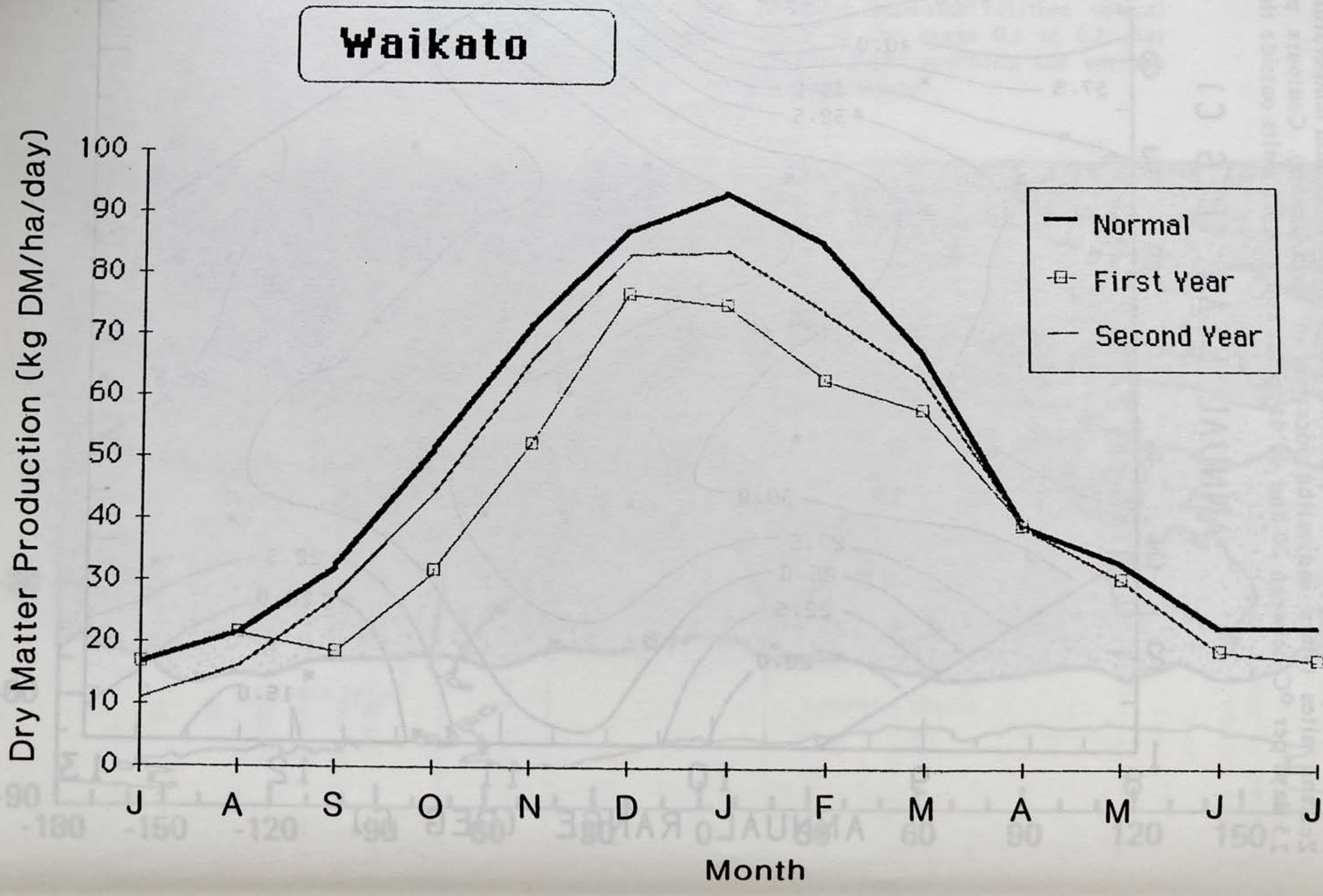
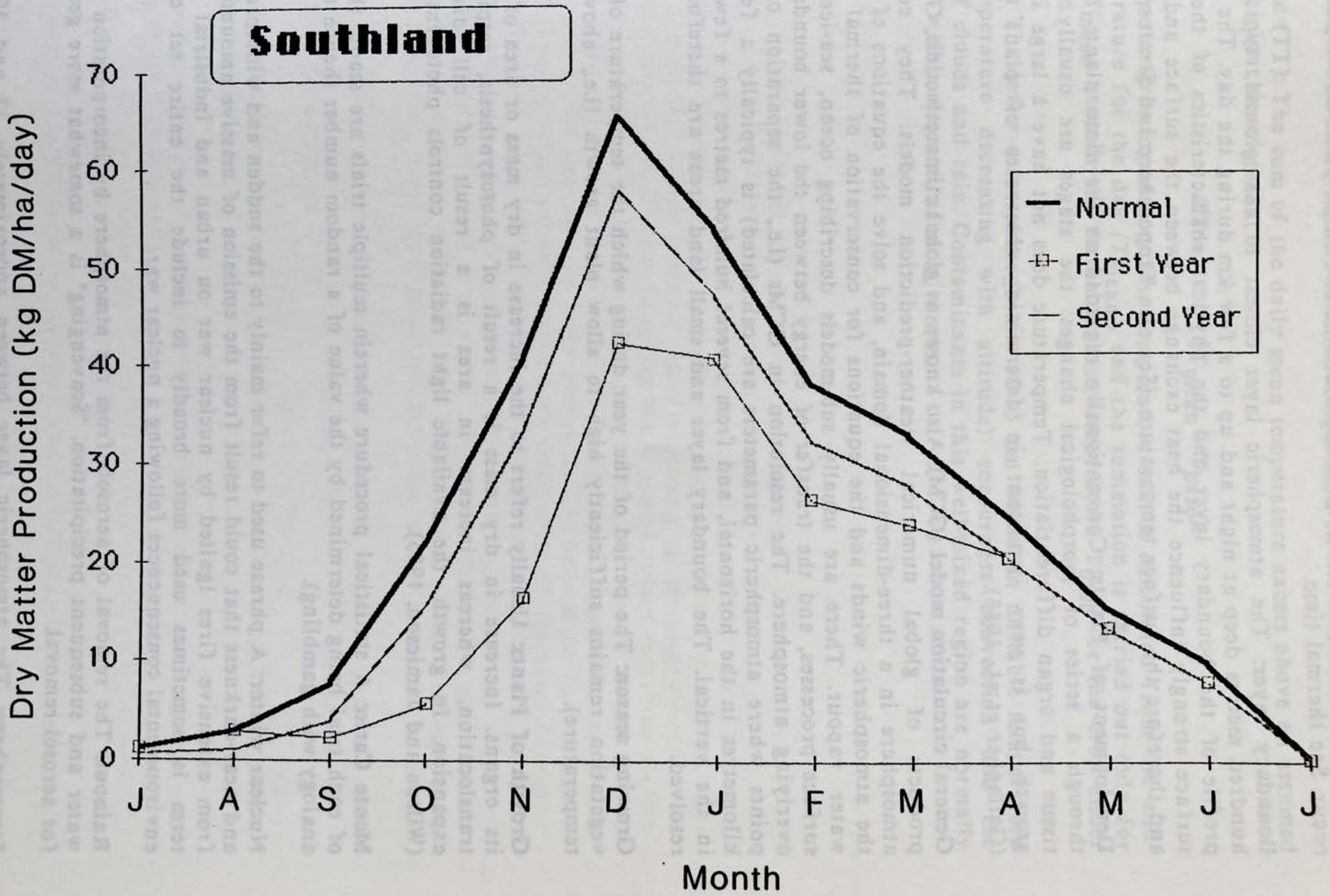


Fig 5: Southland pasture production with temperature reductions of 3°C in spring, 2°C in summer and 1°C for the rest of the year, and 1°C in the second year. (From Baars and Rollo, pers. comm.)



GLOSSARY

Base temperature: A threshold temperature below which plant development does not occur. See thermal time.

Boundary layer: The atmospheric layer closest to the ground, typically several hundred metres deep at night and up to a few km during the day. The temperature profile of the boundary layer and the physical characteristics of the underlying surface strongly influence the heat exchange between the surface and atmosphere and therefore the surface temperature. (See also **Troposphere** and **Stratosphere.**)

Development of Plants: Conventionally regarded as the time plants take to pass through a series of morphological changes: the stages are usually defined by tissue and organ differentiation. Temperature does not have a large influence on growth but is very important in determining the rates of plant development (Gallagher et al., 1983).

General circulation model (GCM): Also known as global climate models, GCMs are by-products of global numerical weather-prediction models. They consider the atmosphere in a three-dimensional domain, and solve the equations of motion for the atmospheric winds and the equations for conservation of thermal energy and water vapour. There are usually sub-models describing ocean, sea-ice and land-surface processes, and the transfer of energy between the lower boundary and the overlying atmosphere. The resolution in GCMs (i.e., the separation of the grid-points where atmospheric parameters are calculated) is typically a few hundred kilometres in the horizontal, and from several hundred metres to a few kilometres in the vertical. The boundary layer and small land areas are therefore not well resolved.

Growing season: The period of the year during which the temperature of cultivated vegetation remains sufficiently high to allow plant growth (i.e., above the base temperature).

Growth of Plants: Usually refers to the increase in dry mass or area of a plant or its organs. Increase in dry mass is a result of photosynthesis, respiration and translocation, whereas increase in area is a result of cell division and expansion. In growth, the available light radiation controls photosynthetic rates (Wilson and Jamieson, 1985).

Monte Carlo: A statistical procedure wherein multiple trials are made, the outcome of each trial being determined by the value of a random number (hence the implied analogy with gambling).

Nuclear winter: A phrase used to refer mainly to the sudden and widespread cooling and near-darkness that could result from the emission of massive amounts of smoke from extensive fires ignited by nuclear war on urban and industrial areas. The term is sometimes used more broadly to include the entire set of adverse environmental consequences following a nuclear war.

Rainout: The removal of aerosols from the atmosphere by incorporation into cloud water and subsequent precipitation. "Scavenging" is a somewhat more general term for aerosol removal.

Stratosphere: The atmospheric layer between approximately 12 and 50 km (but varying somewhat with latitude), lying directly above the troposphere. The stratosphere is characterised by an increase of temperature with altitude (i.e., a "stable" temperature profile) which suppresses vertical motions. The residence time of particles in the stratosphere is much longer than in the troposphere.

Thermal time (TT): The sum of the daily mean temperature excess above an assumed threshold for plant development

$$TT = \sum (T_{mean} - T_{base}),$$

summed over the growing season. The temperature sum is calculated from the mid-range temperature for the day (T_{mean}), and the summation is carried out only for days when T_{mean} exceeds the threshold base temperature T_{base} for the crop under consideration.

Troposphere: The lower atmosphere below 10-15 km where an unstable temperature profile (temperature decreasing with altitude) encourages convection and the formation of clouds and rain. Contaminants in this well-mixed region are normally "washed-out" within days or, at most, weeks.