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EFFECTS OF HUMAN ACTIVITIES ON GLOBAL CLIMATE

A summary, with consideration of the implications of a possibly warmer Earth

by

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Prepared in response to the request addressed to the president of CAS in Resolution 12(EC-XXVIII) and presented to the third session of the Executive Committee Panel of Experts on Climatic Change

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FOREWORD

In response to a request by the Seventh World Meteorological Congress, the WMO Executive Committee at its twenty-eighth session (1976) approved the text of an official WMO statement on climatic change which is reproduced in the following pages, and at the same time allocated responsibilities for promoting and co-ordinating work in three broad components of an integrated international effort related to studies of climatic change. The Commission for Atmospheric Sciences was given the main responsibility in respect of one of these namely, the work on assessing and predicting the effects of geostrophysical processes and human activities on climate.

Dr. William W. Kellogg of the U.S. National Center for Atmospheric Research, a well-known expert in this field, was accordingly requested to prepare a document on the influence of human activities on climate.

Dr. Kellogg's draft was presented to the Executive Committee Panel of Experts on Climatic Change at its third session (February, 1977). The panel agreed that it was a very useful statement of the current state of knowledge of anthropogenic influences on climate, and recommended its publication as a WMO Technical Note after being revised by Dr. Kellogg in the light of comments by panel members and others. The panel pointed out, however, that the views expressed in the report would remain those of the author. The present publication constitutes the Technical Note as recommended by the panel.

I wish to convey the sincere thanks of WMO to Dr. Kellogg for his comprehensive and valuable report and also to the members of the panel and other scientists for their contributions to the final text which it is hoped will stimulate much-needed further research in this field of great interest and concern.



D.A. Davies
Secretary-General

SUMMARY

With the current state of knowledge about how the Earth's climate system operates and about possible external influences, it is difficult to make any predictions for the natural course of the climate in the next several decades. However, climate system models have now developed to the point where it is believed that a second kind of prediction can be made, viz., assuming that no unusually large naturally-induced fluctuation occurs in the interval, the climate will probably respond in a given way for a given change of one or more of the external or boundary conditions of the model. This makes possible a prediction of the course of the climate as a result of anthropogenic influences, other external factors remaining the same.

Experiments with a number of different models with widely varying degrees of complexity have now converged on approximately the same conclusions, namely:

- The largest single effect of human activities on the climate is due to the increase in atmospheric carbon dioxide concentration resulting from burning fossil fuels (coal, petroleum, natural gas), since the additional carbon dioxide gas absorbs infra-red radiation from the surface that would otherwise escape into space, producing an increase in lower atmosphere temperature.
- Virtually all of the other major activities of mankind also contribute to a warming of the lower atmosphere, for example, through injection into the atmosphere of airborne particles ("aerosols") and of other infra-red-absorbing trace gases (such as chlorofluoromethanes, nitrous oxide, etc.), and through the direct addition of heat ("thermal pollution").
- A best estimate of the resultant warming of the mean surface temperature of the Earth due to human activities is about 1°C by 2000 AD (25 per cent increase in atmospheric carbon dioxide) and about 3°C by 2050 AD (doubling of atmospheric carbon dioxide), with an uncertainty of roughly a factor of two. Warming of the polar regions is expected to be three to five times greater than the global average.

These conclusions are based on the assumption that there will be no worldwide effort to curb the use of fossil fuels and that the rate of carbon dioxide release to the atmosphere will continue to increase at a quasi-exponential rate, with only a slightly reduced rate of increase toward the end of the time frame. Since the exchange between the surface and deep waters of the oceans is slow, the decay time of the added carbon dioxide is expected to be between 1000 and 1500 years. Thus, if mankind proceeded to burn all the economically recoverable fossil fuel in the next few centuries, the corresponding increase in atmospheric carbon dioxide concentration would be five to eight times, and this increment would probably remain airborne for many more centuries.

The estimated climate change due to human activities for the year 2000 AD is probably larger than any natural climate change that has been experienced in the past 1000 years or more, and one would have to go back to the period 4000 to 8000 years ago to find a period approaching the degree of warming which is expected by the middle of the next century. A first survey of that past warm period indicates that there was generally more rainfall, especially in the areas of the present subtropical deserts, but that there were some regions at middle and high latitudes where it was drier than now. The warming would almost certainly have a major influence on the extent of Arctic and Antarctic sea ice, and eventually would cause a change in the total volume of the major ice sheets of Greenland and the Antarctic, but the corresponding change in sea level cannot yet be predicted with any confidence.

The question is raised of how the decision-makers of the world can make use of this information, dealing as it does with a probable change that will only become readily apparent after a decade or two. The time scale of the scenario is longer than the planning cycle of most governments and most industries (but not all), and the implications of these future changes in terms of human well-being and national interests are still not clear, necessarily involving value judgements that are beyond the purview of science.

In view of the importance of these probable climatic changes and their societal implications, it is imperative that more effort be devoted to narrowing the areas of uncertainty so that a clearer picture can be drawn of the options still open. It is specifically recommended that research be directed along the following lines:

- Improvement of climate models.
- Quantitative assessment of sources and sinks for carbon dioxide.
- Response of the floating Arctic pack ice to a warming.
- Response of the polar ice sheets to a warming.
- Regional changes of patterns of temperature and precipitation.
- Effects of anthropogenic aerosols on climate.
- Other human influences on climate such as patterns of land use, changes of stratospheric composition, and so forth.

RESUME

En l'état actuel de nos connaissances sur la manière dont fonctionne le système climatique de la Terre et sur les influences extérieures qui peuvent s'exercer sur ce système, il est difficile d'établir quelque prévision que ce soit quant à l'évolution naturelle du climat au cours des prochaines décennies. Toutefois, de telles améliorations ont été apportées aux modèles du système climatique qu'on estime maintenant possible d'établir des prévisions d'une autre nature, c'est-à-dire, dans l'hypothèse où aucune fluctuation d'origine naturelle d'ampleur inhabituelle ne se produira entre-temps, comment le climat réagira-t-il à une modification donnée d'une ou de plusieurs conditions externes ou limites du modèle ? Il est, dès lors, possible de prévoir l'évolution du climat sous l'influence des activités humaines, dans le cas où les autres facteurs externes restent les mêmes.

Les expériences effectuées avec un certain nombre de modèles différents et dont le degré de complexité était fort variable ont maintenant abouti à des conclusions convergentes, à savoir :

- L'effet singulier le plus prononcé qu'ont des activités humaines sur le climat est dû à l'augmentation de la concentration du gaz carbonique dans l'atmosphère, qui résulte de la combustion de combustibles fossiles (charbon, gaz naturel). En effet, en absorbant le rayonnement infrarouge émis par la surface de la Terre et qui, sans cela, se propagerait dans l'espace, les quantités croissantes de gaz carbonique présentes dans l'atmosphère provoquent une hausse de la température de la basse atmosphère.
- Pratiquement toutes les autres activités importantes de l'humanité contribuent aussi à réchauffer la basse atmosphère, notamment par l'injection dans l'atmosphère de particules en suspension (aérosols) et d'autres gaz qui absorbent le rayonnement infrarouge (par exemple chlorofluorométhane, protoxyde d'azote, etc.), ainsi que par le rejet direct de chaleur (pollution thermique).
- La meilleure estimation que l'on puisse donner du réchauffement de l'atmosphère sous l'effet des activités humaines est que la température moyenne à la surface de la Terre s'élèvera de 1°C d'ici l'an 2000 (augmentation de 25 pour cent de la quantité de gaz carbonique dans l'atmosphère) et d'environ 3°C d'ici l'an 2050 (doublement de la quantité de gaz carbonique dans l'atmosphère), l'incertitude étant en gros du facteur 2. On s'attend à ce que le réchauffement des régions polaires soit de trois à cinq fois plus prononcé qu'en moyenne sur le globe.

Ces conclusions reposent sur l'hypothèse qu'aucun effort ne sera déployé à l'échelle mondiale pour limiter la consommation des combustibles fossiles et que la quantité de gaz carbonique libérée dans l'atmosphère continuera à augmenter à un rythme quasi exponentiel qui ne fléchira légèrement que vers la fin de la période considérée. Du fait que, dans les océans, les échanges entre les eaux de surface et les eaux profondes s'effectuent lentement, on estime qu'il faudra de 1000 à 1500 ans pour que le

gaz carbonique supplémentaire apporté à l'atmosphère soit éliminé. Dans ces conditions, si, au cours des tout prochains siècles, l'homme brûle tous les combustibles fossiles économiquement récupérables, la concentration du gaz carbonique dans l'atmosphère augmentera de cinq à huit fois et cet apport de gaz persistera probablement dans l'atmosphère pendant un nombre de siècles bien plus considérable encore.

Le changement climatique attendu en l'an 2000 du fait des activités humaines sera probablement plus grand que n'importe lequel des changements climatiques naturels qui se sont produits au cours du millénaire écoulé ou même au-delà. Il faudrait remonter de quatre à huit mille ans en arrière pour trouver une période caractérisée par un degré de réchauffement voisin de celui escompté pour le milieu du prochain siècle. Une première analyse de cette période de réchauffement antérieure montre qu'elle s'est généralement accompagnée d'une augmentation de la pluviosité, particulièrement dans les zones où se situent actuellement les déserts subtropicaux, mais que, par contre, dans certaines régions des latitudes moyennes et élevées, le climat était plus sec qu'actuellement. Ce réchauffement aurait certainement une influence profonde sur l'étendue des champs de glaces de mer de l'Arctique et de l'Antarctique et modifierait finalement le volume des immenses calottes glaciaires du Groenland et de l'Antarctique, mais il n'est pas encore possible de prévoir de combien le niveau de la mer s'en trouverait modifié.

La question se pose de savoir comment ceux qui, dans le monde, ont pouvoir de décider peuvent utiliser une telle information concernant une évolution probable qui ne deviendra réellement perceptible que d'ici une ou deux décennies. Le scénario se développe sur une période plus longue que le cycle de planification de la plupart des gouvernements et de la plupart des industries (encore qu'il y ait des exceptions) et les répercussions de cette évolution future du climat sur le bien-être des populations et les intérêts nationaux demeurent encore très imprécises, d'autant plus qu'à ce niveau interviennent forcément des jugements de valeur qui sortent du cadre de la science.

Etant donné l'importance des changements climatiques probables et les implications qu'ils comportent pour les sociétés, il faut s'efforcer toujours davantage de restreindre les domaines d'incertitude, afin de dresser un tableau plus précis des options qui restent ouvertes. Il est recommandé, en particulier, d'orienter les recherches dans les directions suivantes :

- Amélioration des modèles climatiques
- Evaluation quantitative des sources et des puits de gaz carbonique
- Conséquences d'un réchauffement sur la banquise flottante de l'Arctique
- Conséquences d'un réchauffement sur les calottes glaciaires polaires
- Changements de la distribution des températures et des précipitations à l'échelle régionale
- Influence des aérosols d'origine humaine sur le climat
- Autres influences exercées par l'homme sur le climat en raison, par exemple, de l'aménagement du territoire, des changements apportés à la composition de la stratosphère, etc.

РЕЗЮМЕ

Состояние существующих знаний о климатической системе Земли и о возможных внешних влияниях на эту систему делает трудной задачу составить какое-либо предсказание естественного развития климата в течение следующих нескольких декад. Однако модели климатических систем разработаны в настоящее время в такой мере, что представляется возможным составить предсказание другого рода, а именно: допуская, что в промежутке не произойдет никаких необычно больших изменений, вызванных природными источниками, климат, очевидно, будет реагировать определенным образом на данное изменение одного или более внешних или пограничных условий модели. Это делает возможным предсказать ход климата в результате антропогенного влияния. При этом предполагается, что другие внешние факторы остаются без изменения.

Эксперименты с большим количеством различных моделей различной степени сложности приводят приблизительно к тем же самым заключениям, а именно:

- Наибольшим единичным воздействием человеческой деятельности на климат является повышение концентрации атмосферной двуокиси углерода, возникающей в результате сжигания ископаемого топлива (уголь, нефть, природный газ), так как дополнительное количество двуокиси углерода поглощает инфракрасное излучение с поверхности земли, которое, в противном случае, уходило бы в космическое пространство, вызывая тем самым повышение температуры в нижней атмосфере.
- Фактически, все другие основные виды деятельности человека также вносят свой вклад в потепление нижней атмосферы, например, в результате поступления в атмосферу взвешенных частиц ("аэрозолей") и других газов, находящихся в виде следов и поглощающих инфракрасную радиацию (таких как хлорфторметаны, окись азота и др.), а также путем непосредственного излучения тепла ("тепловое загрязнение").
- Результирующее повышение средней приземной температуры Земли в связи с человеческой деятельностью оценивается приблизительно в 1°C к 2000 году н.э. (повышение атмосферной двуокиси углерода на 25%) и около 3° к 2050 году н.э. (повышение содержания окиси углерода в атмосфере в два раза) с фактором неопределенности приблизительно равным двум. Предполагается, что потепление полярных районов будет в 3-5 раз большим, чем в среднем в глобальном масштабе.

Эти заключения основаны на допущении, что в мировом масштабе не будет принято каких-либо усилий по ограничению использования ископаемого топлива и что количество поступления двуокиси углерода в атмосферу будет увеличиваться по квази-экспоненциальному закону лишь с небольшим сокращением в конце указанного периода времени. Так как обмен между поверхностными и глубокими водами океана происходит медленно, предполагается, что время распада дополнительного количества двуокиси углерода находится в пределах 1000 и 1500 лет. Таким образом, если человечество будет продолжать сжигать все ископаемое топливо, добыча которого экономически оправдана, концентрация двуокиси углерода в атмосфере увеличится соответствующим образом в 5-8 раз. и это дополнительное количество двуокиси углерода, очевидно, будет оставаться в атмосфере в течение многих веков.

Оцениваемое изменение климата в связи с человеческой деятельностью к 2000 году нашей эры будет, вероятно, большим, чем любое естественное климатическое изменение, имевшее место за прошедшие 1000 лет или более, и для того, чтобы найти период с потеплением приблизительно сходным с тем, которое ожидается к середине следующего века, необходимо изучить климат за последние 4000 или 8000 лет. Первая оценка прошлых периодов потепления показывает, что, в целом, имело место большее количество осадков, особенно в районах существующих субтропических пустынь, но были также районы в средних и высоких широтах, в которых климат был более сухим, чем сейчас. С большой степенью уверенности можно сказать, что потепление оказало бы влияние на состояние арктического и антарктического морского льда и, очевидно, послужило бы причиной изменения общего объема основного ледяного покрова Гренландии и Антарктики, однако соответствующие изменения уровня моря не могут быть предсказаны с достаточной достоверностью.

Возникает вопрос о том, каким образом лица, принимающие решения в мировом масштабе, могут использовать данную информацию, имея в виду при этом, что они имеют дело лишь с вероятным изменением, которое станет абсолютно очевидным через одно или два десятилетия. Временной масштаб предполагаемых изменений больше, чем циклы планирования, применяемые большинством правительств и промышленных кругов (но не всех), и значение этих будущих изменений для благосостояния человека и для национальных интересов все еще не достаточно ясно. Требуется более точные оценки, которые наука пока еще не в состоянии провести.

Учитывая важность этих вероятных климатических изменений и их значения для общества, представляется необходимым приложить больше усилий для того, чтобы сузить области неопределенности и определить более четкую перспективу выбора существующих путей. Конкретно рекомендуется, чтобы исследования проводились в следующих областях:

- усовершенствование климатических моделей;
 - количественная оценка источников и стоков двуокиси углерода;
 - реакция арктического плавающего пакового льда на потепление;
 - реакция полярных ледяных покровов на потепление;
 - региональные изменения в распределении температуры и осадков;
 - влияние аэрозолей антропогенного происхождения на климат;
 - Влияние других видов человеческой деятельности на климат, таких как некоторые виды землепользования, изменение состава стратосферы и т.д.
-

RESUMEN

Con los conocimientos que actualmente poseemos sobre el funcionamiento del sistema climático de la tierra y sobre las posibles influencias externas es difícil hacer cualquier predicción del curso natural del clima en los próximos decenios. Sin embargo, los modelos del sistema climático se han desarrollado hasta tal punto que se estima posible hacer un segundo tipo de predicción, es decir, suponiendo que en el intervalo no se produzcan grandes fluctuaciones anormales de origen natural, el clima probablemente responderá en un sentido dado a un cambio determinado de una o más de las condiciones externas o límites del modelo, lo que hace posible una predicción del curso del clima como resultado de influencias antropogénicas, siempre que no se modifiquen otros factores externos.

Los experimentos realizados con varios modelos diferentes de complejidad muy diversa han permitido llegar en la actualidad a aproximadamente las mismas conclusiones, es decir:

- El efecto individual más importante de las actividades humanas en el clima se debe al aumento de la concentración de anhídrido carbónico en la atmósfera como consecuencia de la combustión de combustibles fósiles (carbón, petróleo, gas natural), ya que el anhídrido carbónico adicional absorbe la radiación infrarroja de la superficie que de otro modo se hubiera liberado en el espacio, produciendo un aumento de la temperatura de la atmósfera inferior.
- Prácticamente todas las demás actividades importantes del hombre también contribuyen a un calentamiento de la atmósfera inferior, por ejemplo mediante la inyección en la atmósfera de partículas en suspensión en el aire ("aerosoles") y de otros gases raros que absorben la radiación infrarroja (tales como los clorofluorometanos, óxido nitroso, etc.), y a través de la adición directa de calor ("contaminación térmica").
- La mejor estimación del calentamiento resultante de la temperatura media de la superficie de la tierra debido a actividades humanas es de aproximadamente 1°C para el año 2000 (un aumento del 25 por ciento del anhídrido carbónico en la atmósfera) y de unos 3°C para el año 2050 (el doble de anhídrido carbónico en la atmósfera), con una incertidumbre de aproximadamente un factor de dos. Se espera que el calentamiento de las regiones polares será de tres a cinco veces mayor que la media mundial.

Estas conclusiones se fundan en el supuesto de que no se desplegarán esfuerzos mundiales para frenar la utilización de combustibles fósiles y de que el ritmo de liberación de anhídrido carbónico en la atmósfera continuará aumentando a un índice casi exponencial, con solamente un ritmo ligeramente reducido de aumento hacia finales del período. Como los intercambios entre la superficie y las aguas profundas de los océanos son lentos, se espera que el período de disminución del anhídrido carbónico añadido se

sitúe entre 1.000 y 1.500 años. Por lo tanto, si la humanidad quemase todos los combustibles fósiles económicamente recuperables en los próximos siglos, el correspondiente aumento de la concentración de anhídrido carbónico en la atmósfera sería de cinco a ocho veces, y este incremento probablemente permanecería en el aire durante muchos más siglos.

Los cambios climáticos estimados para el año 2000 debidos a actividades humanas son probablemente mayores que cualquier cambio climático natural que se haya producido en los últimos 1.000 años o más, y habría que volver al período de 4.000 a 8.000 años atrás para hallar un período que se aproxime al grado de calentamiento que se prevé para mediados del próximo siglo. Un primer estudio de dicho período pasado de calentamiento indica que generalmente se produjo más precipitación, especialmente en las zonas de los actuales desiertos subtropicales, pero que existieron algunas regiones situadas en latitudes medias y altas donde el clima fue más seco que actualmente. El calentamiento tendrá casi con toda seguridad una gran influencia en la extensión de los hielos marinos del Ártico y el Antártico, y eventualmente producirá un cambio en el volumen total de los principales casquetes glaciares de Groenlandia y del Antártico, pero todavía no puede predecirse con ninguna seguridad cuál será el cambio correspondiente del nivel del mar.

Se plantea, por lo tanto, la cuestión de cómo los responsables en el mundo de la adopción de decisiones pueden utilizar esta información, tratándose como en este caso de un probable cambio que únicamente comenzará a percibirse claramente después de uno o dos decenios. La escala cronológica de esta situación es superior al ciclo de planificación de la mayoría de los gobiernos e industrias (pero no de todos ellos), y todavía no están en claro cuáles serán las consecuencias de estos futuros cambios en términos de bienestar humano e intereses nacionales, lo que necesariamente lleva consigo juicios de valor que no son de la incumbencia de la ciencia.

Dada la importancia de estos probables cambios climáticos y sus consecuencias sociales, es imperativo desplegar mayores esfuerzos para reducir los sectores de incertidumbre a fin de poder obtener una imagen más clara de las opciones que todavía se presentan. En especial, se recomienda que la investigación se oriente de acuerdo con las siguientes líneas:

- Perfeccionamiento de los modelos climáticos.
- Evaluación cuantitativa de las fuentes y de las pérdidas de anhídrido carbónico.
- Respuesta de los hielos a la deriva flotantes del Ártico a un calentamiento.
- Respuesta de los casquetes glaciares polares a un calentamiento.
- Cambios regionales de la distribución de la temperatura y la precipitación.
- Efectos de aerosoles antropogénicos en el clima.
- Otras influencias humanas en el clima, tales como planes de aprovechamiento de tierras, cambios de la composición estratosférica, etc.

WMO STATEMENT ON CLIMATIC CHANGE

1. In spite of man's remarkable advances in technology, his economic and social welfare are still highly dependent on climate. Food production especially is significantly affected by variations in climate as evidenced by the decrease in world grain reserves over recent years. This dependence is becoming of even greater importance in the face of the demands of an increasing world population. But it is not only the demand for food which illustrates man's dependence on climate; floods, droughts and extremes of temperature seriously disrupt urban communities, interfere with agriculture, industry and commerce, and hamper economic and social development.
2. Evidence of conditions of the Earth's climate in past decades, centuries, millennia and geological epochs has been deduced from a wide variety of direct and indirect sources. This evidence clearly reveals that climate exhibits variations on all scales of time. Since the climate has been so continuously variable due to natural causes in the past, it must be assumed that it will continue to vary in the future. However, long-term trends in global climate are masked by shorter-term fluctuations and by regional changes; exceptionally wet or warm conditions in one region are often accompanied by unusually dry or cool conditions in another.
3. The recent occurrences in certain regions of climatic extremes persisting for a few weeks, months or even years, such as excessive rain, droughts and high or low temperatures, have led to speculation that a major climatic change is occurring on a global scale, which could involve a transition to one or another of the vastly different climates of past ages. While such a global change could occur from natural causes, the trend towards such a change is likely to be gradual, and would be almost imperceptible. This is because the fluctuations over shorter periods of time are likely to be so much larger as to obscure these long-term trends. It is these shorter-term climate changes, which may be due to natural or man-made causes, that now require urgent attention and further studies.

4. The natural shorter-term variability of climate is becoming of increasing importance as the result of growing pressures on limited natural resources. It is this variability which has been highlighted by the disastrous droughts and weather extremes in many parts of the world which have caused so much human suffering and have adversely affected economic development. It is the changes associated with this variability to which governments could respond if sufficient advance warning could be given.

5. The possible change of climate resulting from man's activities is at least of equal concern. Burning of oil and coal increases the amount of carbon dioxide in the atmosphere and this could produce a long-term warming and, as a consequence, large-scale changes in rainfall distribution. The release of chemicals (for example, chlorofluoromethanes) and the increase in the dust content in the atmosphere as a result of man's activities, if not checked, might also alter the climate. Direct thermal emissions from urban and industrial areas have already affected climate on a local scale and could have wider effects if these emissions were to increase. However, with the present state of knowledge of the atmosphere it is not possible to give an accurate assessment of the magnitude of such changes.

6. Being aware of the importance and urgency of these problems, meteorologists and other scientists have taken steps to improve the quality and accessibility of data relating to past behaviour of the atmosphere, the oceans and other relevant environmental factors; they are seeking to improve the monitoring of current climatic developments and of environmental changes to assess the impact of natural processes and of man's activities; they are endeavouring to intensify research aimed at a better understanding of climatic processes and the impact of climatic variability on the natural environment and on human activities.

7. In view of the increasing importance of the inherent shorter-term variability of climate to many human activities greater use should be made of existing knowledge of this variability in planning for economic and social development; for example, an assessment of the probability of occurrence of rainfall within given ranges can provide an assessment of the viability of proposed agricultural or hydrological projects. If the results of further research by meteorologists and other scientists reveal that man's activities could produce changes in climate having serious consequences for mankind, political and economic decision makers would be faced with additional problems, as described in paragraph 5. Further research in climatic change is therefore of the greatest importance.

8. In summary, the present views of WMO on climatic change and its study are as follows:

- (a) Although in the long-term, a major natural change to a different climatic régime must be expected, it is unlikely that any trend towards such a change would be perceptible in the short term as it would be obscured by the large shorter-term climatic variability;
- (b) The shorter-term natural or possible man-made changes in climate are of immediate concern because of their important impact on human welfare and economic development;
- (c) An improved ability is needed to predict short-term natural changes in climate to enable governments to consider appropriate action;
- (d) Improved understanding of and improved ability to predict the impact of man's activities on the global climate is needed in view of their possible consequences;
- (e) Existing knowledge of natural short-term climatic variability, although limited, should be used more effectively in planning economic and social development.

June 1976

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1. INTRODUCTION

1.1 Purpose of this report

There has been an understandable reluctance on the part of the scientific community to openly engage in debate on the controversial and sometimes agonizing question of the extent to which we, mankind, may influence the world's climate. Nevertheless, it is already clear that the issue is unavoidable, and that we must lock horns with it.

Recognizing this, the World Meteorological Organization (WMO) has taken a number of steps to obtain advice on matters of climatic change generally, and anthropogenic influences on climate in particular. This report is one of those steps. (See Foreword to this document by the Secretary-General.) It was prepared to help the WMO's Executive Committee Panel of Experts on Climatic Change in its continuing consideration of these important matters, and is being distributed as a WMO Technical Note (on the recommendation of the Panel) in order to enlarge the arena of the discussion.

It should be emphasized that the assumptions and conclusions contained in this document will probably not meet with universal agreement, and that responsibility for them must rest with the author. However, the case has been carefully studied and documented, as will be seen, and therefore does represent an attempt to express a kind of consensus of those who have thought the most about climatic change and possible future human influences on it.

The author has felt free in this effort to draw material from a forthcoming book ("Climate Change," edited by John Gribbin, Cambridge University Press), in which he has a chapter covering many of these same subjects.

We cannot leave such a review of the physical factors involved in future climatic change without at least touching on some of the social and political implications. Physical science is still not able to provide answers for most of these societal implications, involving as they do "value judgments," but nevertheless we can attempt to present a probable scenario of the future so that the decision makers of the world can begin to formulate their various value judgments. That is, we believe, the ultimate purpose of this report.

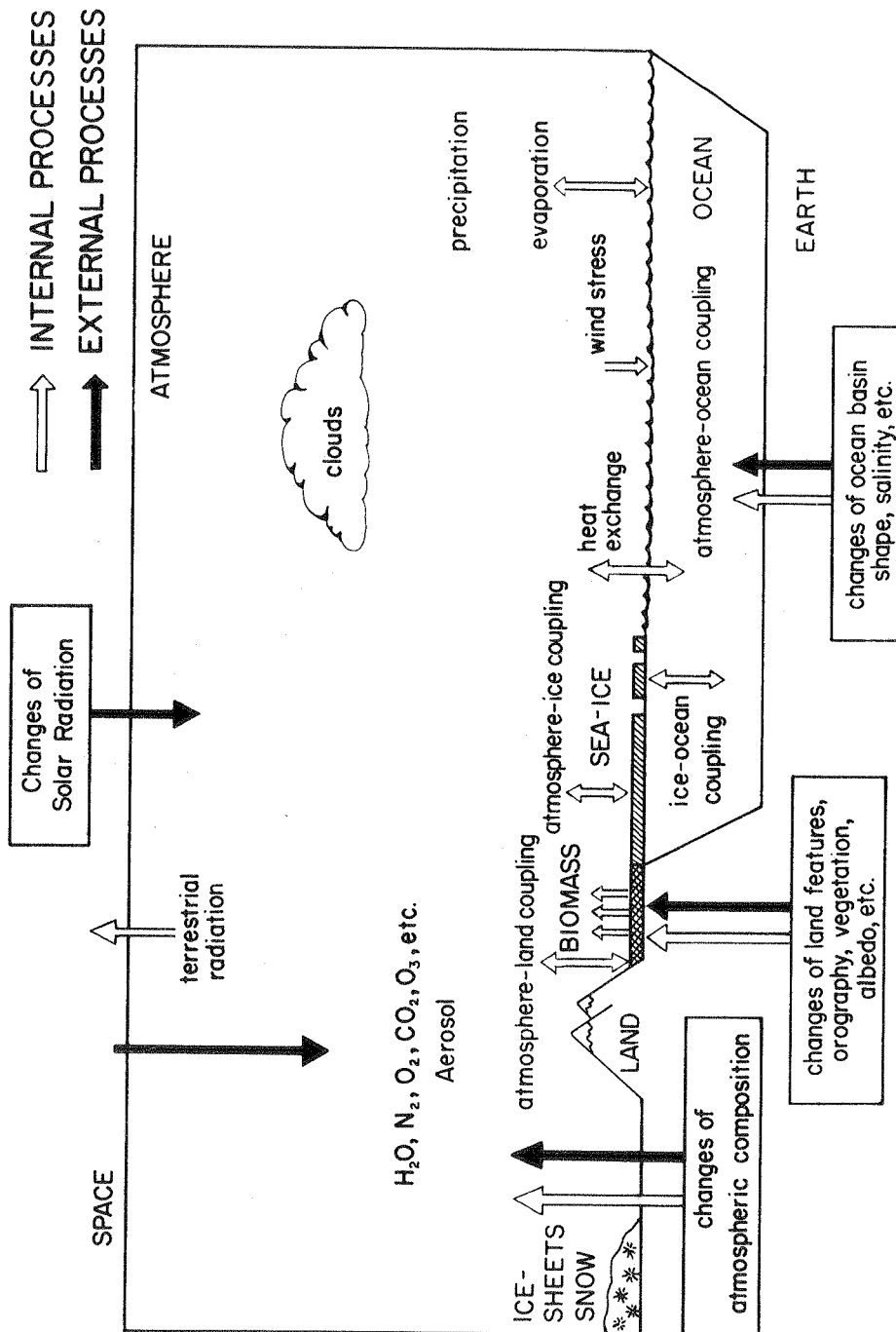


Figure 1. Schematic representation of the interacting components of the coupled atmosphere-ocean-ice-land surface-biomass climate system. [Adapted from Figure 3.1, GARP-16 (1975).]

1.2 Climate change and its predictability

A great deal has been said about the predictability of weather and climate. For example, roughly half of the appendices in GARP-16 (1975) refer in one way or another to the matter. [The reference here is to the WMO/International Council of Scientific Unions (ICSU) report on "The Physical Basis of Climate and Climate Modelling," the result of a major international conference sponsored by the Joint Organizing Committee for the Global Atmospheric Research Program (GARP).] Two discussions there that are particularly illuminating and incisive are Appendix 2.1 (by E. N. Lorenz) and 2.2 (by C. E. Leith); and it appears that the rather pessimistic view of Lorenz prevailed when the Summary was being written, which says: "...we are at present not able to tell what kind of future climate changes are likely to occur nor can we assess the extent to which man himself may inadvertently cause such changes."

If we believed that statement to be literally true, we would not pursue the subject of this report any further. However, Lorenz himself makes an important distinction between two kinds of predictions. First, he considers the prediction of changes in the statistics of the ensemble of different states of the atmosphere due to the many interactions within the climate system itself. A second kind of problem is the prediction of how these climate statistics will change as a result of an alteration in the external or boundary conditions of the system, as illustrated schematically in Figure 1.

It is generally conceded that prediction of the first kind is going to be extremely difficult; it may even prove to be theoretically impossible. It seems clear that we will never be able to forecast day-to-day weather for more than a few weeks in advance. If no significant periodicities exist in the behavior of the climate (other than the 24-hour and 12-month periods), we will not be able to predict its course either for periods longer than the longest decay time of an important component of the system. For example, the upper levels of the oceans may turn out to be the internal component in our models with the longest "memory." Depending on the depth of ocean considered, this "memory" is on the order of a few months to a few years, compared to the atmosphere's relaxation time or "memory" of about three days (Namias, 1974). Similarly, ice and snow cover may prove to have some year-to-year "memory" which could be taken into account. But even granting that these components have some sort of "memory," their prediction and incorporation into climate models will be no simple matter. Thus, the outlook for developing a useful long-term capability to predict the natural variation of climate on a time scale of years to decades seems rather dim.

Prediction of the second kind (to use Lorenz's term) is a different matter. Our present climate models can simulate the long-term equilibrium climate with some realism when current boundary conditions are used. If changes in boundary conditions take place slowly over time periods much longer than the response time of the system, then the climate should be always quite close to equilibrium. We can therefore use our climate models to take successive "snapshots" of the system as it slowly responds to changing boundary conditions. (We would not need to assume such a near-equilibrium state if we could specify the relaxation time of the system after impulsive forcing. However, the changes which we will be considering will generally be relatively small and slow, so that the equilibrium approximation will usually suffice--two exceptions being the uptake of carbon dioxide by the world's oceans and the response of the great ice sheets of Greenland and Antarctica, as will be pointed out.)

Two elements are needed if such predictions of the second kind are to be useful and credible. We must be able to specify a response function of matrix which relates changes in climate parameters to given changes in boundary conditions. And we must have faith that these changes will be unique, that is, that only one stable equilibrium climate corresponds to one set of boundary conditions. To borrow Lorenz's terminology again (Lorenz, 1970), we must believe that the system is "transitive."

The concept of intransitivity or "almost intransitivity" that Lorenz has so deftly injected into recent discussions of climate predictability (Lorenz, 1970) hangs like a black cloud over those who are seeking to throw some light on the study of human influences. There is the theoretical possibility that a system as complex and interactive as the climate system may have several "solutions" corresponding to a single set of boundary conditions. Which of these the real atmosphere will choose would then be a matter of chance. Indeed, it might be possible for the climate to remain in one state for some time, and then spontaneously jump to an alternate state with no change in the forcing functions or boundary conditions. Some of our climate models have these characteristics, but we are not really sure to what extent this rather disquieting theoretical possibility plays a real role in the prediction of climate.

However, most of our current models do possess stable steady-state solutions. They may, in fact, be unrealistically stable. Lorenz has noted (GARP-16, 1975, p. 136): "A final shortcoming of all models so far considered...is that they are too deterministic." Even the most physically complex three-dimensional time-dependent ones settle down after a suitable period (depending upon the amount of upper ocean included) to a condition where the ensemble mean statistics no longer change with time as long as boundary conditions are fixed.

Leith is apparently not depressed by Lorenz's "black cloud," and takes a more pragmatic view of predictions of the second kind. He says (GARP-16, 1975, p. 140), "For sufficiently small changes about the present climate we would expect a linear analysis to be appropriate, and in mathematical terms the problem becomes one of determining a response matrix whose elements are sensitivity coefficients. For larger changes, of course, second-order effects become important and a linear analysis is inadequate, but many questions of climate stability could be answered from a knowledge of the linear response matrix.... The slowly changing ensemble mean we may call a signal which we may hope to be able to predict through the use of climate models. The practical value of such predictions will depend in the usual way, of course, on the ratio of signal to noise," where the noise in this case may (for time dependent models) be the unpredictable daily or seasonal-mean fluctuations.

Many of these arguments will be familiar to the readers of this report, and we would not review them here were it not for the fact that there are those who prefer to be extremely conservative in their views on predictability--even predictability of the second kind.

There is still another reason for being conservative, and that is the fact that there are at least two (and possibly more) interactions or feedback loops in the real climate system that we do not know how to include properly in our climate models. They are the cloudiness-temperature-albedo loop, and the atmosphere-ocean circulation-sea surface temperature loop (SMIC, 1971; GARP-16, 1975).

For the time scales involved in our predictions of the second kind (a decade to a century) it is very probable that the upper levels of the oceans and not the deep oceans will be involved, and the response time of these upper levels to a warming will be shorter than for a cooling, and probably not more than a few years. The most probable effect of the oceans, therefore, will be to slow any change of mean surface temperature because of their large heat capacity--a small damping of that change. (Their role in taking up excess carbon dioxide is a separate matter that will be taken up in Section 2.2.2.)

As for amount of cloudiness and its response, we cannot be sure that it will not exert an important influence on a climate change, and we do not even know the direction of the feedback--whether positive (amplifying) or negative (damping). Changes in the middle or high clouds would have relatively small effects in any case, since their influence on the heat budget due to the albedo change is roughly cancelled by their influence on the outgoing infrared radiation; but, on the other hand, changes in low cloudiness can have an

appreciable effect on albedo without a compensatory infrared effect (Manabe, 1971; 1975; SMIC, 1971; Schneider, 1972). Experiments with general circulation models, such as that of the U.S. National Center for Atmospheric Research (NCAR), in which clouds are a variable internal parameter (Schneider and Gal-Chen, 1973) and empirical studies of the response of satellite-determined cloudiness to changes in temperature (Budyko, 1975; Cess, 1976; White and Chylek, 1977) all indicate that the amount of cloudiness responds rather weakly, and the feedback effect must therefore also be weak. There is some evidence from modeling experiments suggesting that cloudiness may provide a mild positive feedback in the tropics when a major part of the tropical oceans are warmed or cooled, but a negative feedback when the sea surface temperature of a limited area is changed--in the latter case clouds form preferably over a warm area, raising the albedo and reducing the solar radiation available at the surface (Chervin, private communication).

In view of the above we can argue with some conviction that ignoring cloudiness as a feedback mechanism will not greatly invalidate the results of climate modeling experiments and prediction of the second kind. Nevertheless, we are gratified to see that the GARP Joint Organizing Committee (JOC) has repeatedly stressed the need for research in this area and has called for an integrated study of Cloudiness and Radiation Budget, part of which is called STRATEX, in cooperation with the IAMAP Radiation Commission and Commission on Cloud Physics (JOC-XII, 1976, p. 8).

1.3 The growing magnitude of human interventions

Regional climate change in large cities and industrialized areas is an accepted fact. There are now sizeable areas, of 10^3 to 10^4 km² or greater, where the heat released by human activities is more than 10 percent of the amount of solar radiation absorbed at the surface (SMIC, 1971) and urban "heat islands" can have temperatures at night and in winter that are many degrees warmer than the surrounding countryside.

Furthermore, either as a result of the extra heating or the addition of cloud condensation and freezing nuclei, convective precipitation downwind from such cities as Chicago, St. Louis, and Paris has been significantly increased (Dettwiller and Changnon, 1976).

There is much talk of building "power parks," where a very large electric generation capacity would be concentrated in one limited area of a few square kilometers--partly for efficiency, partly for security. In the U.S. and Europe up to 10 Gw installations are being planned, and we understand that even 100 Gw power parks are starting to be seriously considered. Assuming that at least half of this power will be released in the form of heat rather than electricity, the 100 Gw power parks begin to be comparable in thermal energy release to the Surtsey volcano, a savannah brushfire, or a large thunderstorm (Hanna and Gifford, 1975). (See also discussion by Flohn in App.1.2, GARP-16, 1975).

It is therefore evident that those concerned with environmental changes must already take note of the effects of human activities on regional scales, but the subject of this report is still larger scales of change. Here we have no very persuasive evidence that a global climate change has already come about as a result of human activities, but when we consider the rate of growth of these activities it seems only a matter of time--how long? that is the question.

To emphasize this point we will repeat a few well known statistics: World population is increasing at about 2 percent per year (it is less in the more industrialized countries), energy and other resources going into food production are increasing at 3 to 4 percent per year (though famine seems to persist in many places), and world energy use is increasing at roughly 6 percent per year, possibly more (eg. SMIC, 1971; Häfele, 1974). Current total world energy production is about 10×10^3 Gw (10 Tw), and we can compare this with the 8×10^7 Gw rate of absorption of solar energy at the surface, a factor of almost 10^4 more. The reason that the total energy use is rising faster than the population is obviously due to a growing per capita energy use, which is currently about 2.5 kw (it is highest in the U.S.A., - 10 kw). A recent study indicates that this per capita energy use may now be rising at more than 5 percent per year (Kahn et al., 1976).

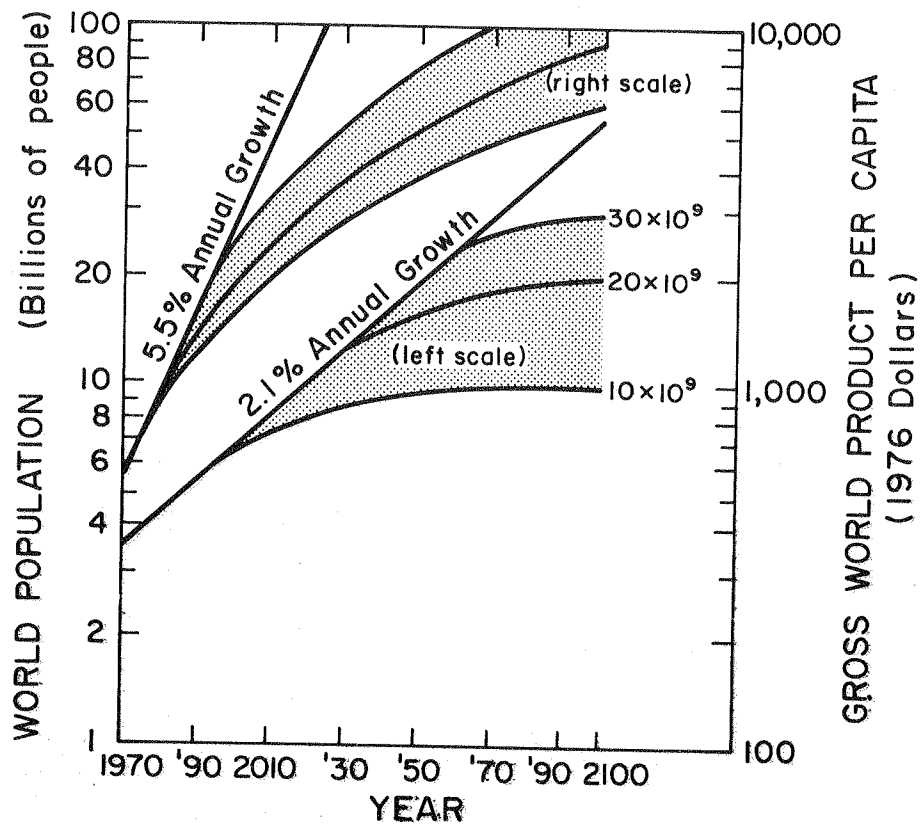


Figure 2. A set of possible projections of world population and gross world product (GWP) per capita. The GWP per capita follows approximately the scenario described by Kahn et al. (1976, Figure 5, p. 56). It will be noted that these curves tend toward a leveling-off or steady state, which is obviously more realistic than any continued exponential growth. Nevertheless, they should not be taken as "predictions," but rather as a rough indication of the time scale involved in any such evolutionary process.

What can we say about the future trends? One obvious remark is that exponential increases cannot continue indefinitely, so the pertinent questions relate to the limits to growth and the time scales involved. Figure 2 illustrates what we mean. This is presented to show the sort of time scale involved if there is to be an orderly leveling out to a "post-industrial society," as some call it. It shows that the transition from the present period of maximum growth to some sort of steady state must be completed by the end of the next century, unless there are catastrophes such as a major nuclear war or very widespread famines. There seems to be a growing optimism on this matter among "futurists," and even the relatively conservative Club of Rome at its meeting in Philadelphia in April 1976 concluded that a successful growth transition of this sort could take place in a major part of the world (though some countries would probably not succeed).

We will not belabor this point further, but it is the basis for an important assumption that we will have to make in our scenario of the future: Societal growth will continue for the next few decades at only slightly diminished rates, but it will level off in a little more than 100 years. This assumption will have other ramifications that we will bring up in the appropriate places, such as the future availability of fossil fuels.

1.4 Societal attitudes toward climate change

As we have mentioned, the thought that mankind could influence the entire climate of the planet on which it lives is a disturbing one. Those who subscribe to the "environmental ethic" fight to preserve what remains of wilderness areas, tidelands, and other unspoiled spots on the earth, and there is a growing sense of tribal guilt over the inroads of human technology on nature. Many, especially in the younger generation, express real alarm over the advances of technology and seek a limit to material growth and a return to some sort of simpler society; and there are well informed and responsible scientists who share in this concern, believing that the ecological system of the world (which includes mankind as just one component) cannot stand much further imbalance (eg., Holdren and Ehrlich, 1974; Heilbrunner, 1974).

In such an atmosphere of apprehension it is especially important, we believe, for those who are wrestling with the question of our impact on climate to do our homework as carefully as possible and to report our conclusions clearly and objectively, along with our assumptions and the uncertainties involved. If we conclude that the evidence favors a prediction of inadvertent climate change, its implications must also be spelled out.

Climate change cannot be said to be either "good" or "bad" until we understand better what we mean by those words, and, even then, there will be a value judgment. Furthermore, we can expect that some people will be better off and others worse off, so such broad generalizations could very well be meaningless anyway.

This, too, will be a point to which we will return in Section 4.

2. A SCENARIO OF MANKIND'S INFLUENCE ON CLIMATE

2.1 Predictions of the second kind

In Section 1.2 we discussed the distinction between the problem of trying to predict natural climate change or fluctuations and the problem of trying to predict what would happen to the climate with a given change of a boundary condition. It is the second kind of prediction that we are dealing with here, and it is necessary to say something at the outset about how the task has been approached.

All the influences on climate that we will be dealing with, with one or two minor exceptions, operate through a change in the heat balance of the system (See Figure 1). The simplest question that can be posed about the climatic effect of such an influence is: What will be the change in mean surface temperature for a given change in the external or boundary conditions? ("External" is used here in the special sense of being excluded from the internal and interacting processes in the climate model being used. What may be external in one model, such as sea surface temperature or snowcover, may be internal in a more physically comprehensive model.)

To answer this question it is not unreasonable to start by employing a globally-averaged model of the earth and atmosphere, one in which the mean surface temperature and corresponding vertical temperature (and humidity) profiles are related by globally-averaged vertical transfers of sensible and latent heat and radiation, and constrained by a set of assumptions about how these must take place. Radiative-convective models of the sort used by Manabe and Wetherald (1967), Rasool and Schneider (1971), and Ramanathan (1975) are all examples of the globally-averaged approach, in which great attention is usually paid to the calculation of radiative transfer by trace gases in the atmosphere (CO_2 , H_2O , O_3 , CFMs, etc.), and vertical transfers of heat and water vapor (latent heat) are taken care of by the assumption of a constant lapse rate and relative humidity up to the tropopause. This assumption is justified by the observation that the real atmosphere does seem to adjust itself this way over most of the range of latitudes and seasonal changes--as indeed do the more complex three-dimensional models.

The obvious deficiency of such an approach lies in the fact that it neglects some feedback loops that are almost certainly important, notably the polar ice-albedo-temperature and cloudiness-albedo-temperature loops--plus whatever might change in the ocean circulations. The magnitude of the first of these loops has been estimated by several people, and when included seems to add 25 to 50 percent to the surface temperature response of a globally-averaged (or zonally-averaged) model that does not include it (Schneider, 1975; Cess, 1976; Manabe, App. 2.4, GARP-16, 1975; Lian and Cess, 1977).

Zonally-averaged energy-balanced models that include the latitude dependence of surface temperature, albedo, incoming and outgoing radiation, and so forth, are the next most complex models that have been used for predictions of the second kind. Meridional transport of energy is generally parameterized (empirically) in terms of the meridional temperature gradient. A rather wide range of assumptions concerning vertical transports have been used, and some have even attempted to include cloudiness as an internal parameter. In such models, the polar ice-albedo-temperature feedback loop can be included. Examples of this approach are the pioneering models of Budyko (1969), Sellers (1969), Saltzman (1967), and Adem (1970), and the more recent models of Sellers (1973), Stone (1973), North (1975), Weare and Snell (1974), and Temkin and Snell (1976).

Attempts have been made to introduce the longitudinal dimension into highly parameterized energy-balanced models, but it is not yet clear whether these can tell us much more than the zonally-averaged ones. The next real step upward seems to require that atmospheric dynamics and eddy transports of heat and momentum be considered more explicitly, since then one can begin to study the interplay between continents and oceans and their effects on meridional transport by meridional circulations and planetary scale waves. Early examples of such attempts are those of Eliassen (1952) and Smagorinsky (1964), and others have been made by Dickinson (1971), Saltzman and Vernekar (1972), Kurihara (1970) and Wiin-Nielsen (1970). For a detailed discussion of these various models the reader is referred to Schneider and Dickinson (1974), or a shorter version by the same authors in GARP-16 (App. 2.3, 1975). For reasons that are not apparent, few if any of these highly parameterized dynamic models have been used for climate experiments to determine sensitivities to effects of human activities.

Three-dimensional time-dependent general circulation models (GCMs) of the atmosphere have now been developed at a number of institutions, and these have been so extensively discussed in the literature that we will not attempt a review of them here. [See, for example, NAS (1975) App. B by Gates; Manabe, App. 2.4 in GARP-16 (1975); or Smagorinsky (1974).] The main points that need to be made when these GCM-type models are used for

experiments of the second kind are these: The models need to be run each time long enough so that their ensemble statistics no longer change with time, and the variances of these statistics must be well established so that the experimental "noise" is known (Chervin et al., 1974); it is necessary to make a number of control runs to establish the stability (transitivity) of the model, and preferably a number of perturbation runs must be made also; and, finally, a large amount of computer time must be used.

Some early climate experiments with GCMs have been criticized because not enough attention was paid to the statistical design of the experiment, but considerable advance has now been made in understanding how to use GCMs appropriately (Chervin et al., 1976; Chervin and Schneider, 1976). In most GCM experiments to date, however, the solar radiation is held constant (a perpetual July or January) due to the exorbitant computer costs involved in running them for several years, and this means that many questions relating to the march of seasons cannot yet be properly studied with them, such as the annual cycle of Arctic sea ice and the transitional periods of the Asian monsoon. An even more serious deficiency of most current GCMs is that they do not include a coupled ocean, but sea surface temperature is proscribed--it is an external parameter. This means that there is no overall energy balance, and so they cannot respond properly to a change in heat input to the climate system.

Only one group has done climate experiments with a GCM coupled to an ocean, and in this case the ocean was simulated by a non-circulating "swamp" with no heat capacity (but an infinite supply of water). These experiments by the U.S. Geophysical Fluid Dynamics Laboratory have been reported by Smagorinsky (1974), Manabe and Wetherald (1975), Wetherald and Manabe (1975), and Manabe (App. 2.4, GARP-16, 1975), and we will have occasion to refer to them again.

It can be seen, then, that there is an entire hierarchy of models of the climate system, and many of them have been used in experiments "of the second kind" to show how the system would respond to a given change in an external condition. It is reassuring to see that, when we compare the results of experiments with the same perturbations (for example, one percent more solar radiation, or double the CO₂ content) but using different models, the response is generally found to be either about the same or differs by an amount that can be rationalized in terms of recognized model differences or assumptions. Of course, it is possible that all our models could be utterly wrong in the same way, giving a false sense of confidence, but it seems highly unlikely that we would still be so completely ignorant about any dominant set of processes (see Section 1.2). We must simply recognize and admit where our models are deficient, and then factor that into our statement about the uncertainty in their responses.

Models are, indeed, the only tools we have available now to predict the response characteristics of the real atmosphere-ocean-earth system. In a hundred years or so we may finally know the outcome of our inadvertent "experiment" with the original prototype, but by that time the climate changes, whatever they turn out to be, will have been a fait accompli.

2.2 Specific processes

In this section we will take up the various individual processes in the climate system that may be influenced by mankind. In each case we will attempt to make an estimate of the response of the climate system (with emphasis on surface temperature and secondarily precipitation), an indication of the time scale involved in the change, and some measure of uncertainty in our estimate. To be "significant" an artificially induced change of global climate must be larger and more persistent than the natural quasi-random fluctuations that are to be expected in the same time frame, and we will make such a significance test in Section 2.3.

2.2.1 Release of heat

The climate is governed by the heat balance of the climate system, so it is clear that the direct addition of an appreciable quantity of heat in any form will cause a change in climate, notably the mean temperature and probably the atmospheric circulation patterns as well. In some of the large cities of the world, especially those at high latitudes where there is relatively less sunlight, the amount of heat released per square meter is equal to or even greater than the average flux of sunlight absorbed at the surface during the year. However, on a regional scale (order of 10^5 km^2) this ratio is rarely more than a few percent, and on a global basis the total amount of heat released by all of mankind's activities is only slightly more than 10^{-4} of the solar energy absorbed at the surface (SMIC, 1971; Kellogg, 1974; 1975a; 1975b). Such a small fraction as we will see, would have a negligible effect on the total heat balance of the earth.

The future course of human activities and the rate at which this release of heat will increase depends on factors that are hard to assess. In Section 1.3 we discussed the basis for what appears to be a not unreasonable assumption, namely, that societal growth will continue for the next few decades at only slightly diminished rates, but that it will tend to level off in a little more than 100 years. Again, we refer to Figure 2 as a way of visualizing such a scenario and its time scale, keeping in mind the empirical fact that per capita energy consumption and per capita gross national (or world) product are linearly proportional to a good approximation (Singer, 1975).

Let us see what the "leveling off point" suggests in terms of total heat release. If we take a 20 billion population (5 times the present) and an average per capita energy demand of 20 kw (roughly 10 times the present world average, and twice that of the United States), the total is $4 \times 10^5 \text{ Gw}$, or 0.5 percent of the solar energy absorbed at the surface. Such a level, it appears, could hardly be attained prior to 2100 AD (if at all)--and we will not attempt a projection beyond that.

This large amount of heat would presumably be released over the continents where the people will be, and that would give an uneven distribution of heating as seen on a global scale and produce marked regional effects and changes in the large-scale circulation patterns (Washington, 1972; Llewellyn and Washington, 1977). We can, however, assume that this heat will end up being more or less evenly distributed in a given hemisphere and then use our climate models to estimate the effects that this would have on mean surface temperature. Since most of the heat will be released at or near the surface, the additional heat can be considered (in these model experiments) as if it were an increase in the total amount of solar radiation reaching the surface. There is not precise agreement among the various climate models (Schneider and Dennett, 1975; Gal-Chen and Schneider, 1976), but the current set of models seem to converge quite well on the answer that a 1 percent increase in the heat available to the system would result in about 2°C increase in the mean surface temperature, probably within better than a factor of two (Wetherald and Manabe, 1975; Budyko, 1969; 1972; Sellers, 1969; 1973; Saltzman and Vernekar, 1972). Thus, the average surface temperature increase might be about 1°C by the end of the next century due to the direct release of heat.

All of the climate models that we have cited relating heat input to the system to surface temperature take into account the polar ice-albedo-temperature feedback mechanism, and they show a marked increase in the sensitivity of the polar regions. The change at latitudes above about 50° , therefore, will be larger than the 1°C , and in the polar regions can be expected to be 3 to 5 times larger. This increased sensitivity of the polar regions to climate change has been well recognized from studies of the real atmosphere as well as from model experiments (eg., SMIC, 1971; Lamb, 1972; van Loon and Williams, 1976a; 1976b; Budyko, 1971; Borzenkova, 1976). That is a point that will have to be stressed again.

2.2.2 Carbon dioxide

Since the beginning of the Industrial Revolution more than a century ago we have been taking carbon out of the earth in the form of coal, petroleum, and natural gas and burning it, in the process making carbon dioxide and water vapor--plus heat, which is of course our main reason for doing it. Of the carbon dioxide that has emerged from countless chimneys and exhaust pipes, about half is still in the atmosphere and the other half has been dissolved in the oceans or has gone into the earth's biomass--the biomass being mostly the forests.

The carbon dioxide in the atmosphere has risen from an estimated 280 or 290 parts per million by volume (ppmv) to the present 325-plus ppmv, and it is estimated, based on the early studies of Revelle and Suess (1957) and Bolin and Ericksson (1959), that it will reach some 380 to 390 ppmv by 2000 AD (Machta, 1973; Machta and Telegades, 1974; Ekdahl and Keeling, 1973; Bacastow and Keeling, 1973; Broecker, 1975), and may double by the next mid-century, even assuming a slackening in the rate of increase of fossil fuel consumption (Bacastow and Keeling, 1973; Baes *et al.*, 1976).

Figure 3 depicts the past history of the carbon dioxide concentration and how it is expected to increase in the future. It will be noted from the records at Point Barrow, Mauna Loa, and the South Pole that there is a couple of years' lag between the northern hemisphere (where most of the carbon dioxide is released) and the southern hemisphere, as would be expected because of the slow exchange of air between hemispheres. Also, the slope of the curves are not exactly constant, there being a slackening in the mid-1960s followed by an acceleration in the 1968 to 1971 period. Since worldwide release of carbon dioxide cannot have changed much from its steady rise of about 4 percent per year (SCEP, 1970; Baes *et al.*, 1976), the explanation for these fluctuations in carbon dioxide rate of increase probably lies in fluctuations of the rate of uptake by the oceans (Bacastow, 1976).

The chief concern that we have with this changing component of the atmosphere is its effect on the heat balance, since carbon dioxide is virtually transparent to solar radiation but absorbs outgoing terrestrial infrared radiation in several infrared bands, radiation that would otherwise pass through the atmosphere and escape to space. The additional carbon dioxide enhances the absorption of this radiation, thereby warming the lower atmosphere, and reradiates part of it back downward, thereby warming the surface. The result, therefore, of an increase in carbon dioxide is an increase in surface temperature, accompanied by a corresponding decrease in stratospheric temperature that keeps the total outgoing infrared radiation at the top of the atmosphere constant (Schneider and Kellogg, 1973).

There have been a number of model calculations to show the influence of carbon dioxide on the surface temperature, some globally averaged one-dimensional models such as that of Manabe and Wetherald (1967), and some latitude-dependent and with the oceans taken into account crudely (Sellers, 1974; Manabe and Wetherald, 1975; Manabe, App. 2.4, GARP-16, 1975). These various results have been reviewed most recently by Schneider (1975) and Budyko and Vinnikov (1976). A representative set of estimates follows in Table 1 (and we have more or less arbitrarily set the degree of uncertainty at plus or minus a factor of two, even though the model results are now converging better than that).

These surface changes, it should be emphasized, refer to the weighted average (by surface area) for the globe. Both observed changes of climate and climate models indicate that at high latitudes, above about 50° latitude, any climate change would be expected to be larger, and in the polar regions from 3 to 5 times larger than an average change such as those shown in the table (perhaps even more in winter) (SMIC, 1971; Sellers, 1974; Manabe and Wetherald, 1975; van Loon and Williams, 1976a; 1976b; Borzenkova *et al.*, 1976).

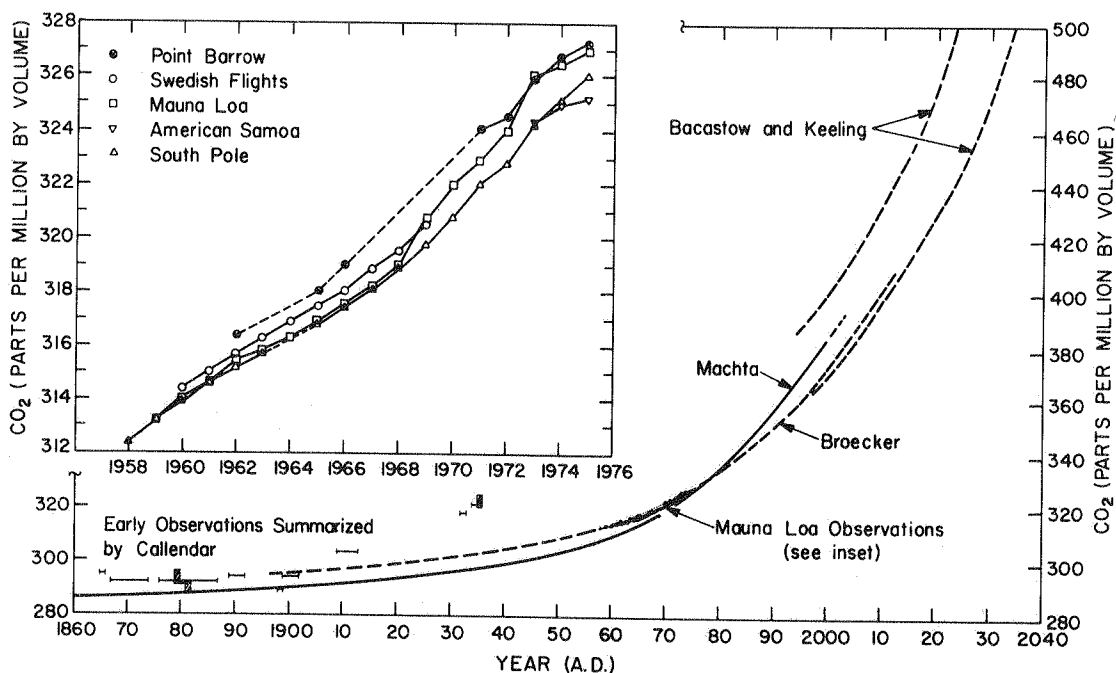


Figure 3. The record of carbon dioxide concentration from 1860 to 1975, measured at several locations, and some estimates of future trends. The early data were critically reviewed by Callendar (1958) and subsequently reevaluated by Barrett (1975). The current series of observations for Mauna Loa are those reported by Keeling *et al.* (1976a) and C. D. Keeling (private communication), for South Pole by Keeling *et al.* (1976b) and Keeling (private communication), for American Samoa and Point Barrow by NOAA (1975) and T. Harris (private communication), and for the Swedish aircraft observations by Bolin and Bischof (1970). Note that the carbon dioxide concentrations are given in terms of the "adjusted index values" (for the sake of continuity with the earlier data); it may be necessary to adjust these values upward by about 3 to 4 ppmv, according to Keeling *et al.* (1976a), to obtain the correct mole-fraction, but this would not affect the slopes of the curves. The model calculations predicting future carbon dioxide increases by Machta (1973), Broecker (1975), and Bacastow and Keeling (1973) all take account of the takeup of anthropogenic carbon dioxide by oceans and the biomass (but in somewhat different ways), and assume a quasi-exponential increase in the rate of burning of fossil fuels (notably coal) in the next half-century or more. It is expected that in this time period about half of the new carbon dioxide released will remain in the atmosphere; and due to the slow mixing of deep ocean waters with the upper layers the decay time of the added carbon dioxide, were we to stop producing it, is estimated to be 1000 to 1500 years.

Table 1

Effects of Adding Carbon Dioxide to the Atmosphere

Factor of Change of Carbon Dioxide from Present	Expected Time for Change to Occur	Mean Surface Temperature Increase
+25%	2000 AD	0.5 to 2°C
+100%	2050 AD	1.5 to 6°C

One question is frequently raised about the continued escalating use of fossil fuels, as envisioned in this scenario, and that is their availability. While natural gas is expected to become much less easily available by the turn of the century, and some sources of petroleum will have also been nearly exhausted, the world's coal reserves are so large that, even at an increased rate of consumption, they will probably last for several centuries--though it may be harder and therefore more expensive to dig it out as time goes on (see, for example, Hubbert, 1971; Singer, 1975; Kahn et al., 1976; Häfele, 1974; Weinberg and Hammond, 1970; SCEP, 1970). It is estimated that if all the economically recoverable fossil fuel were eventually burned in the next few centuries the atmospheric CO₂ content would rise to 5 to 8 times its pre-Industrial Revolution value (Keeling, 1977; Singer, 1975; Baes et al., 1976; Siegenthaler and Oeschger, 1977).

While the model calculations of the mean surface temperature increase corresponding to a given increase in CO₂ concentration have only been carried to the point of a doubling of CO₂, the relationship appears to be approximately logarithmic. Thus, for every doubling one would expect another 2.5 to 3°C warming. Some scenarios have extended the calculation beyond our time frame, and if the rate of burning of fossil fuel continues to escalate (as at present) the second doubling of CO₂ will occur before 2100 AD (Keeling, 1977; Siegenthaler and Oeschger, 1977), and that would produce a 5 or 6°C warming. Recall, again, that polar temperature rises would be several times the global average.

The main sink for CO₂ in the longer run will be the oceans (Keeling, 1973; 1977; Bolin, App. 8, GARP-16, 1975; Oeschger et al., 1975), since the forests of the world cannot go on increasing indefinitely--on the contrary, they are quite possibly being cut down faster than they can grow. The oceans contain about 60 times more CO₂ than the atmosphere, but in order for them to come into a new equilibrium with a larger atmospheric content there has to be an exchange between the upper levels of the ocean (variously taken to be 100 to 1000 m deep on the average) and the deep ocean water. This process, it has been estimated, takes at least 1000 years, and Keeling (1973; 1977) estimates a decay time for atmospheric CO₂ of 1500 years. (It would not matter for our purposes if he were wrong by a good many hundred years.) Thus, even if, by some determined and unlikely measure, we could stop releasing CO₂ from fossil fuel in the next century, we would still find the incremental CO₂ lingering in the atmosphere at a very slowly diminishing concentration for many centuries.

In the brief discussion above we have not attempted to give the complete picture of the carbon cycle, and especially the processes that account for takeup of CO₂ by the upper ocean layers and the subsequent exchange of this water with the deep ocean reservoir. The interested reader is referred to, for example, Bolin, App. 8 in GARP-16 (1975) or Oeschger et al. (1975) for a critical discussion of the subject.

2.2.3 Chlorofluoromethanes

A contaminant added to the atmosphere in the past few decades by mankind in large quantities, one that has been most notorious for its possible effect on the ozone layer in

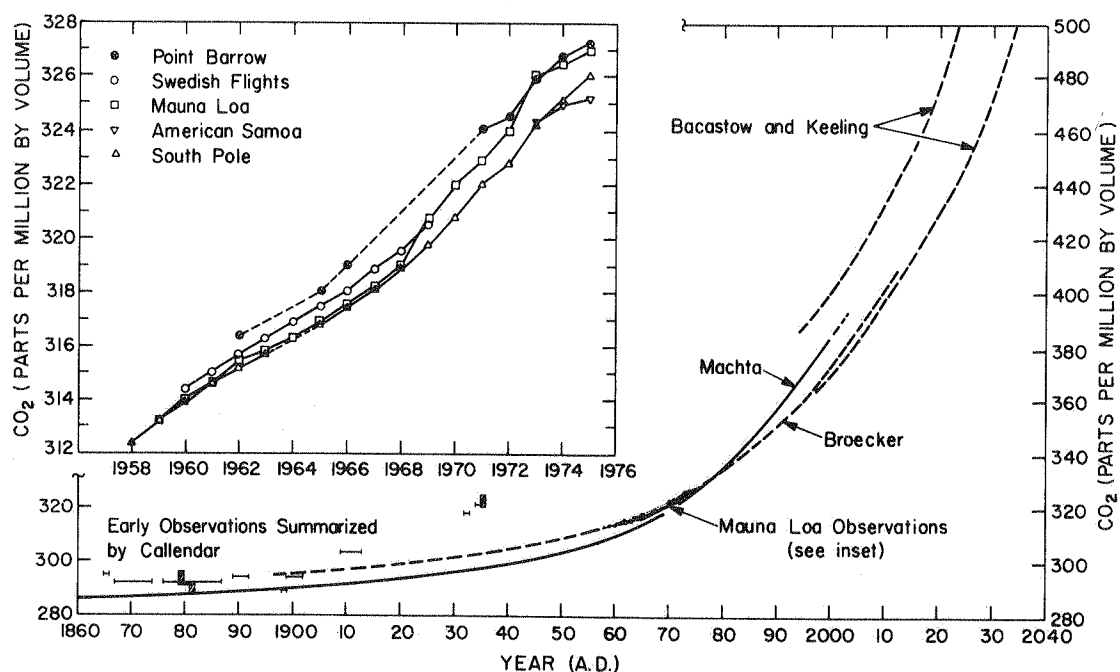


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2.2.3 Chlorofluoromethanes

A contaminant added to the atmosphere in the past few decades by mankind in large quantities, one that has been most notorious for its possible effect on the ozone layer in

the stratosphere, are the chlorofluoromethanes, referred to as FC-11 (CFCl_3) and FC-12 (CF_2Cl_2). (They are sometimes also referred to as "freons," but that is a trade name.) These gases, used both for refrigerants and as aerosol propellants, are extremely stable, nontoxic, and persist in the troposphere for very long periods of time (about 40 yr mean residence time for FC-11, 70 yr for FC-12), and the observed buildup of the FCs in the lower atmosphere suggests that virtually all of the gas released to date can still be found resident in the troposphere. There are probably small sinks at the surface and in the troposphere, and there is a long-term sink in the stratosphere, since those molecules that diffuse upward into the stratosphere are broken down by the ultraviolet radiation there (Crutzen, 1974; Rowland and Molina, 1975; Wofsy *et al.*, 1975; NAS, 1976).

While we will not comment here on the effect of these compounds on the ozone layer (though this is, in a broad sense, a change of the environment), it turns out that they have a direct effect on the temperature balance of the atmosphere that has only recently been identified (Ramanathan, 1975). Like carbon dioxide, the FCs have absorption bands in the part of the infrared "window" between about 8 and 15 μm where there is relatively little water vapor absorption. Thus, the FCs prevent some of the infrared terrestrial radiation from the surface that would otherwise escape to space from passing through the lower atmosphere. The result is an increase in the surface temperature and a corresponding decrease in the stratospheric temperature.

The present mean tropospheric concentration of total FCs is about 0.2 parts per billion by volume (ppbv), and calculations by Crutzen and others indicate that, if FCs continued to be produced at the 1973 production rates, FC-11 would reach about 0.32 ppbv and FC-12 about 0.58 ppbv by 2000 AD, and would level off in the middle of the next century at about 0.7 and 1.9 ppbv respectively (NAS, 1976, Table 5). This quasi-steady state would result in a decrease of outgoing infrared radiation from the troposphere of some 0.3 percent and an associated mean surface temperature increase of 0.5°C , based on Ramanathan's model calculations (which we will take to be correct to better than a factor of two). If, on the other hand, the worldwide production rate of FCs continues to increase at about 10 percent per year, as it has in the past (Howard and Hanchett, 1975), and the total concentration of FCs were to increase to 3.5 ppbv, then the temperature rise would be about 1°C . We cannot say exactly when this would be (since it would depend on the actual production rate), but it is not inconceivable that it could occur as early as 2000 AD.

Projections of the future use of FCs will depend very much on the passage of legislation (or spontaneous reaction by industry or consumer resistance) in various countries limiting the use of FCs as propellants in spray cans. At present roughly one half of the production is in the United States, where such legislation is being seriously considered. In any case, it is likely that the FCs will continue to be used extensively as refrigerants, for which they are probably ideally suited, and it would be difficult (if not unnecessary) to prevent the continued escape of some FCs into the atmosphere. The issue of whether or not there will be a worldwide ban on their use will probably rest with their effect on stratospheric ozone rather than with their effect on climate, since there are identifiable biomedical effects of decreasing ozone (and increasing solar ultraviolet radiation) that are probably cause for real concern (NAS, 1976).

2.2.4 Nitrous oxide and other infrared absorbing gases

We have noted the marked increases in surface temperature that can be produced by large-scale releases of carbon dioxide and the chlorofluorocarbons, the effect being due to their ability to absorb infrared radiation in the atmospheric "window" and their long persistence in the troposphere. This suggests that we should be alert to the buildup of any other trace gases that have similar properties, and there are a great many of them.

One such trace gas is nitrous oxide (N_2O), which is mainly maintained at its present tropospheric concentration of about 0.28 ppmv by biological decay and conversion processes taking place in soil and in the oceans--processes referred to as "denitrification." It has been suggested that the increasing use of nitrate fertilizers by mankind may accelerate the biological production of N_2O and raise its atmospheric concentration (Crutzen, 1976; McElroy *et al.*, 1976), with implications for both surface temperature increase and stratospheric ozone concentration decrease. The amount of this increase in N_2O concentration is still uncertain, since estimates vary from a trivial increase to as much as a factor of 2 in the early part of the next century. The latter would produce a warming on the order of $0.5^\circ C$ (Yung *et al.*, 1976), but this may be considered as an estimate on the high side until we understand the global nitrogen cycle better, and specifically the relative productions by ocean and land (soil) biota.

As an example of the complex interrelationships that one uncovers when one looks under one of these climatic stones, we will mention the fact that in the denitrification process by soil organisms the ratio of N_2 to N_2O produced depends on soil acidity. In slightly alkaline soil only about 5 percent of the gaseous nitrogen compounds released is N_2O , but in acid soil it can increase to over 20 percent. Thus another human activity that we will deal with in the next section, the production of SO_2 and sulphates from burning fossil fuels, will add still further to the production of N_2O as "acid rain" increases the soil acidity downwind from the industrialized areas of the world. However, so far as we know no one has pursued this point to determine how important it could be.

2.2.5 Aerosols

Another product of human activity is the particles that are produced by industry, power generation, automobiles, space heating, slash-and-burn agricultural practices, and so forth. These particles, commonly known as aerosols, are obvious additions to the atmosphere of the large cities of the world, where they are largely produced by a combination of coal burning (which results in both soot and sulphur dioxide, the latter becoming sulphate particles after a short time) and the creation of particles from unburned hydrocarbons in the atmosphere by photochemical reactions in the presence of solar ultraviolet radiation. Such secondary particles (sulphates and hydrocarbons) tend to be somewhat smaller in size than the directly produced smoke or soot particles, though after they have existed for a while in the air they attach themselves to each other and to the larger particles, forming particles that are a combination of both--and it has been demonstrated that the nuclei around which secondary particles form are often soot particles (NSF, 1976).

There is little doubt that since the turn of the Century there has been an increase in the rate at which aerosols have been produced by mankind, particularly in the more industrialized countries (see, for example, SMIC, 1971; Pivovarova, 1970; Machta and Telegadas, 1974; Ellsaesser, 1975; Bryson, 1974; Cobb and Wells, 1970; Budyko and Vinnikov, 1973; Mitchell, 1974; 1975; Dyer, 1974), and many non-urban stations (but definitely not all) have recorded some long-term upward trends in the total aerosol content. If this is so, then one must ask how extensive the anthropogenic aerosols really are, and what their effect will be on the regional or global radiation balance if the upward trend were to continue. (The possible influence of agriculture on wind-blown soil (and sand) aerosols will be touched on at the end of this section.)

Aerosol particles can both scatter and absorb sunlight, and they also absorb and reemit infrared radiation to a more limited extent. When a non-absorbing particle scatters solar radiation some of the scattered radiation will be directed upward as well as downward, and the upward component will be lost to space. This results in less sunlight reaching the earth and an increase in the net albedo of the atmosphere-earth system, which would cause a net cooling. However, when a particle absorbs some of the solar radiation it heats the particle and the air around it, and the effect of this is to reduce the net albedo. Theory tells us that in order to decide whether lower atmosphere aerosols cause an increase in the net albedo (cooling) or a decrease (warming) we must take into account

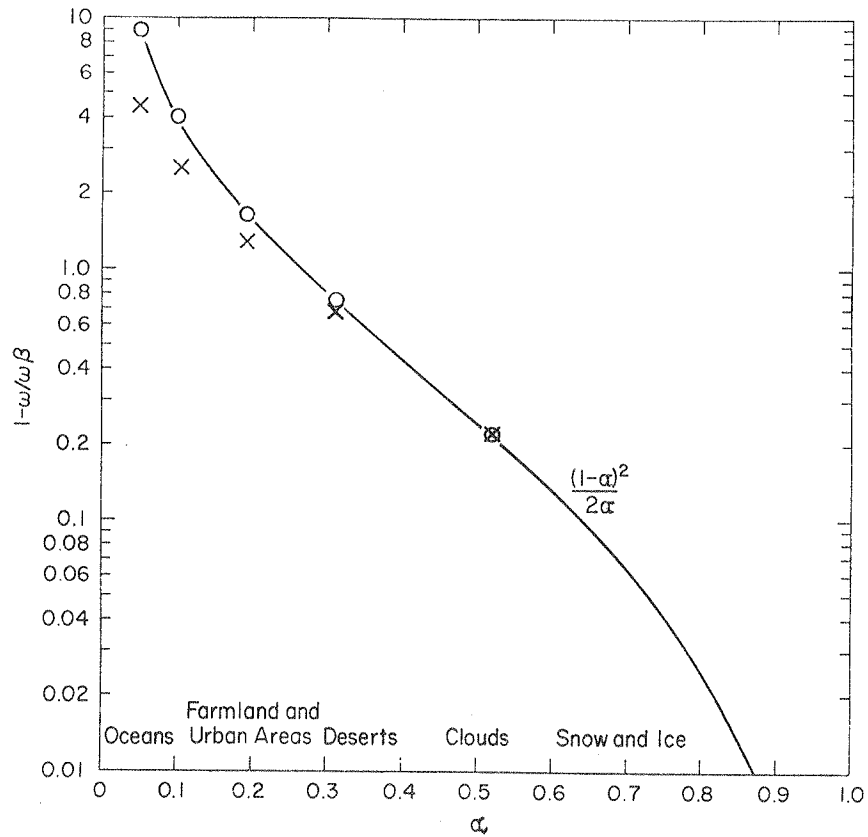


Figure 4. Critical ratio of solar radiation absorption to average upward-scattering cross sections $[(1-\omega)/\beta\omega$ or a/b] as a function of surface albedo (α). The curve with circles represents results of the radiation model of Chylek and Coakley (1974), which takes account of solar radiation only; for conditions represented in the domain above this curve there will be a decrease in the net earth-atmosphere albedo as a result of the aerosols, and consequently a warming. The "x" symbols represent a typical case, calculated by Coakley (private communication), in which both solar and infrared effects are combined, showing that the infrared effects tend to enhance the warming influence of aerosols.

the ratio of the particle absorption to its backscatter, which we will call a/b , and also the albedo of the underlying surface (Mitchell, 1971a, 1971b; Schneider and Kellogg 1973; Chýlek and Coakley, 1974; Coakley and Chýlek, 1975; Weare et al., 1974). When aerosols of a given a/b are over a dark surface, such as the ocean, they are more likely to increase the net albedo than when they are over a light surface, such as a snowfield or a low cloud deck--or over land generally. This relationship is summarized in Figure 4, calculated by Chýlek and Coakley (1974).

There has been a widely shared belief that anthropogenic aerosols generally cause a cooling, the argument being that when spread evenly around the earth their effect over the dark oceans is to increase the albedo and thereby prevent some of the sunlight from being absorbed by the earth-atmosphere system (Rasool and Schneider, 1971; Yamamoto and Tanaka, 1972; Bryson, 1974; Bryson and Wendland, 1975; Bolin and Charlson, 1976; Budyko and Vinnikov, 1973; Mitchell, 1975). Recently, however, it has been pointed out that most of these anthropogenic aerosols exist over the land, near where they are formed, and that they are sufficiently absorbing to reduce the albedo rather than increase it (Kellogg et al., 1975; Eiden and Eschelbach, 1973; NSF, 1976; Weiss et al., 1976; Brosset, 1976).

In Figure 5 (adapted from Kellogg et al., 1975) a theoretical global distribution of mankind's industrial aerosols is shown, assuming that the production in each country is proportional to gross national product, and that the aerosols drift with the surface winds and remain in the atmosphere with a mean residence time of 5 days before they are rained out or washed out or directly deposited at the surface (Moore et al., 1973; Martell and Moore, 1974). It will be noted that their distribution is very uneven, being mostly confined to the industrialized regions of the northern hemisphere, though a certain portion does drift out over the Atlantic and Pacific Oceans, and a considerable part of Europe's "gross national pollution" drifts over North Africa, particularly in the wintertime. (Details of this analysis are given in the referenced report.) These industrially related aerosols absorb more solar radiation than natural aerosols, and their a/b values are generally large enough so they will probably lower the albedo of the atmosphere-earth system over the land, and thereby cause a warming (See Figure 4). However, largely due to our lack of quantitative knowledge of the optical characteristics of these aerosols and their distribution, we cannot yet assign any number to this warming effect. (This problem is discussed by Junge in App. 9 of GARP-16 (1975).)

There are other effects that aerosols may have on the climate of a region, especially its rainfall. In a later section we will discuss their role as condensation and freezing nuclei, which may be significant; and another effect that may be significant is their influence on the stability of the lower layers of the atmosphere. Since, as has been pointed out, they absorb a certain amount of solar radiation, the upper part of a low-lying aerosol layer will be warmed, and the absorption and scattering processes will cause a decrease in the solar radiation reaching the ground. The result is a warming of the upper part of the aerosol layer (in the daytime) and a decrease in the rate of warming at the ground, and this causes the stability of the atmosphere near the ground to be larger than it would be in the absence of the aerosol particles. Bryson and Baerreis (1967) have suggested that the radiational effect of aerosols may decrease convective-type precipitation, especially in sub-tropical places such as Northwest India; and Wang and Domoto (1974) and Atwater (1975) have investigated the effect theoretically. Unfortunately, again we do not yet have enough information about the optical properties of aerosols to make a quantitative evaluation of this influence on rainfall.

Before leaving the effects of anthropogenic aerosols on the radiation balance, there is one more point that may be important but has often been overlooked. Clouds have a fairly high albedo or reflectivity, as is obvious, but theoretical calculations involving the scattering and absorption of plain water droplets indicate that they ought to be more reflective than they are in fact (Twomey, 1972; Liou, 1976). The difference is thought to be due to the presence of absorbing aerosol particles, and the decrease in reflectivity will occur whether the particles are included within the cloud droplets or are floating between them (Ackerman and Baker, 1977). Since the apparent reduction of reflectivity is

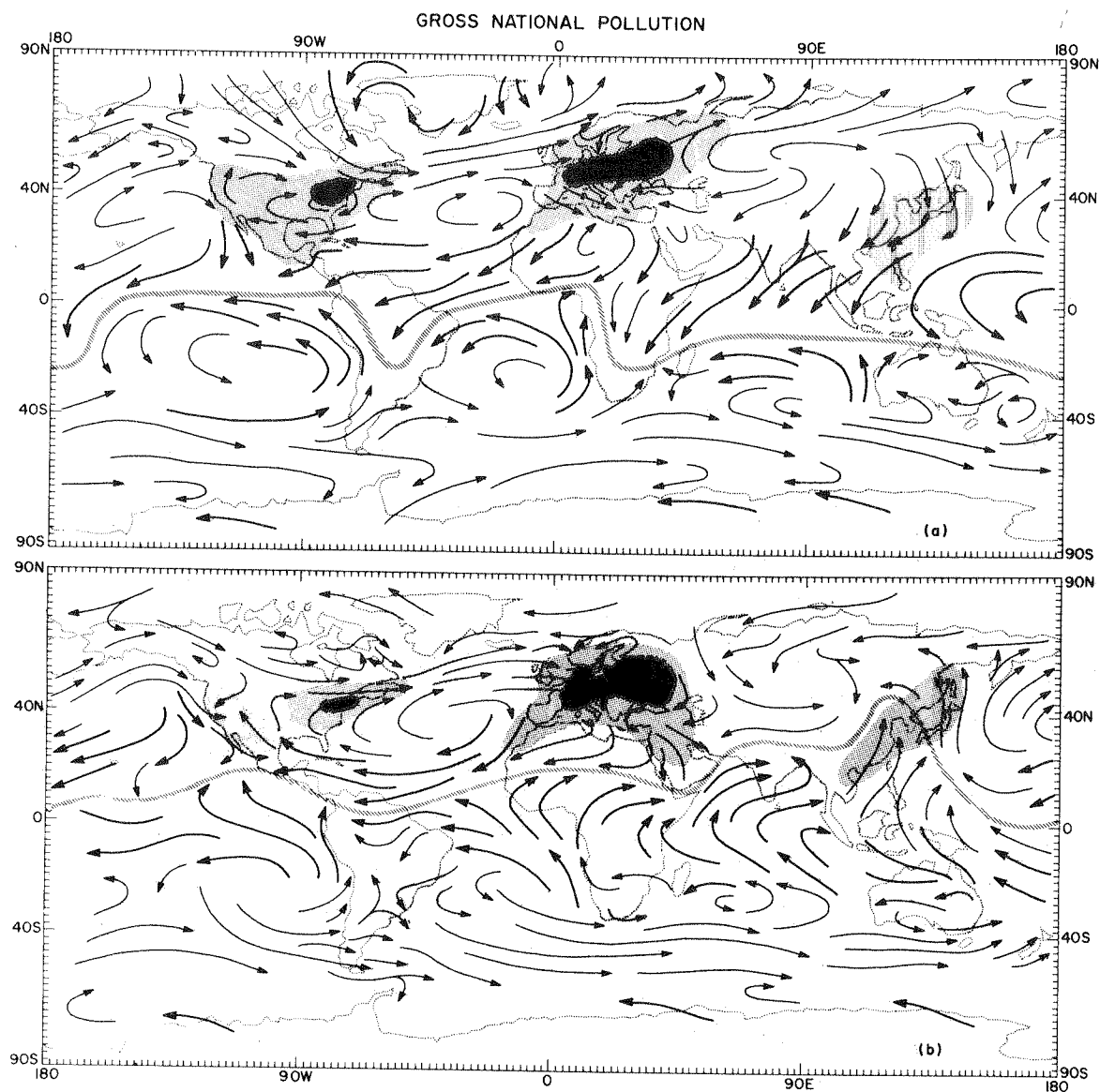


Figure 5. Estimated global distributions of anthropogenic (industrially-related) aerosols, based on the assumptions that production rate is proportional to gross national product of each country, a mean residence time of 5 days, and transport by surface winds [taken from Lamb (1972)] for January (a) and July (b).

quite marked (10 to 20%), it is clear that any increase in absorbing aerosols will cause additional absorption of solar radiation by the clouds, and this represents still another source of heating if anthropogenic aerosols are added to the lower atmosphere.

Industrial aerosols, probably because they are so very obvious to the eyes of the population in large cities, have been the target of vigorous attempts to control them. The result is that in many cities of the world the aerosol content, particularly of larger particles, has shown a definite decrease (Ellsaesser, 1975; NOAA, 1975). The same cannot in general be said for the total aerosol content of the atmosphere observed in Europe and the eastern United States, where secondary aerosol production of smaller sub-micron particles, especially sulphates from the sulphur dioxide produced by burning high sulphur fuels, have become a dominant factor in regional air pollution (Weiss et al., 1977). It should be noted that the practical problems posed in these regions by the ecological and health effects of increasing quantities of sulphate particles probably far outweigh their influence on the regional climate (e.g., Bolin et al., 1971), but that is beyond the scope of this report.

When we consider "anthropogenic aerosols" the fact cannot be ignored that mankind's agricultural practices and the grazing of domesticated animals has an effect on the amount of wind-blown mineral dust or soil. Exposing previously vegetated ground allows the wind to raise fine particles (notably Loess, which consists of material already carried by the wind in earlier times), and Flohn (GARP-16, App. 1.2, 1975; private communication) estimates that human activities may now account for a major source of mineral dust in the air due to the large areas under cultivation (about 35×10^6 km²) or subject to overgrazing (about 5×10^6 km²) (See also SMIC, 1971; Bryson and Baerreis, 1967). Wind-blown particles are generally less absorbing of solar radiation than industrial or slash-and-burn particles (Grams et al., 1974), so the above arguments about the probable warming influence of industrial aerosols may not apply to such mineral dust particles. We know of no quantitative estimate of their overall influence on global climate.

2.2.6 Changes affecting the precipitation process

a) Condensation and freezing nuclei

Many of the aerosols produced by industry have the property of acting as condensation nuclei or freezing nuclei--that is, they can initiate the formation of cloud droplets or hasten the freezing of cloud droplets at temperatures below 0°C. Notable among freezing nuclei sources are steel mills and lead compounds from automotive exhausts. Also, the most common kind of aerosol produced by burning coal and fuel oil, sulphates, are very good condensation nuclei.

While the effect of these condensation and freezing nuclei on the precipitation process are bound to be significant regionally, and while it has been clearly demonstrated that precipitation has indeed increased down-wind from certain cities such as Saint Louis, Chicago, and Paris (Dettwiller and Changnon, 1976), it is difficult to assess quantitatively the effect of these activities even on a regional scale. We must merely, for the time being, recognize this potential effect as a very real one (Hobbs et al., 1974; Schaeffer, 1975).

b) Krypton-85 from nuclear power generation

There are a number of radioactive gases that are released into the atmosphere from nuclear power plants and from the plants that reprocess nuclear fuel. Notable among these are tritium, with a half life of 12.5 years, and krypton-85, with a similar half life of 10.7 years. Krypton-85 is a noble gas that remains more or less permanently in the atmosphere without undergoing any chemical combinations, so it builds up in the atmosphere, subject only to its slow radioactive decay.

When a krypton-85 atom disintegrates it produces an energetic electron that ionizes the air in its vicinity. There are other sources of ionization in the lower atmosphere, such as cosmic rays and the radioactive products of uranium, notably radon and its decay products. As the concentration of krypton-85 builds up in the troposphere, assuming a continued increase of the use of nuclear power in the world, the ionization from this source will begin to compete with all the other natural radioactive and cosmic ray sources. One estimate has been made of this effect, and the prediction is that there will be a 10 to 15% increase in the total ionization or conductivity of the lower atmosphere in about 50 years (Boeck et al., 1975; Boeck, 1976).

Such a change in the ionization of the atmosphere would have little or no direct effect on living things that we can identify (the level of krypton-85 discussed by Boeck is 100 times less than the maximum permissible airborne concentration in unrestricted areas), but if the conductivity of the lower atmosphere is increased one may expect that there will be an effect on the fair weather electric field, which is maintained by all the thunderstorms of the world acting together as a direct current generating mechanism. This electrical system is in effect a global spherical condenser, with a positive charge in the upper atmosphere (the outer shell, which is a good conductor) separated from a negative charge on the earth (the inner shell) by the relatively non-conducting lower atmosphere. The lower atmosphere is not a perfect insulator, however, and a steady leakage of current takes place from upper atmosphere to the ground that must be just balanced by the upward countercurrents produced in the thunderstorms. If the conductivity of the lower atmosphere were increased due to krypton-85 ionization, as suggested by Boeck, then the leakage between the two regions would be increased and (as when a condenser is partially discharged) the electric field would be decreased--unless the thunderstorm generators worked correspondingly harder. Actually, there is good reason to believe that the efficiency of the thunderstorm charge separation process depends in part on the fair-weather electric field (Sartor, 1969), so a decrease in this electric field would probably decrease the rate at which the global generating mechanism worked to maintain it--a positive feedback.

Taking this argument one step further, it is generally believed that the process that initiates rain formation, especially in thunderstorms, is enhanced by the existence of strong electric fields in the clouds, and these electric fields in the clouds (closely related to the global recharging processes just discussed) are activated in part by the fair weather electric field that was there before the cloud formed (Sartor, 1967; 1969). Thus, it has been hypothesized that a decrease in the fair weather electric field would decrease the rate of electric field generation in clouds, and that this in turn would result in a decrease in the rate of formation of precipitation and perhaps a weakening of the cloud dynamical processes as well (Ney, 1959; Vonnegut, 1963; Kellogg, 1975c; Markson, 1975).

Unfortunately, these processes are not understood quantitatively, and it is impossible at this time to assign any value to the effect of an increase in conductivity or a decrease in the fair weather electric field on precipitation--though we would guess that it would be a negative effect. Any such change on a global scale would also affect the heat balance, since thunderstorms account for a major part of the vertical exchange of heat and momentum at low and middle latitudes (Palmén and Newton, 1969).

2.2.7 Patterns of land use

There are many ways by which mankind can influence the heat balance of the earth, and the one that he has been working at longest is the alteration of patterns of vegetation. When a forest is cleared for a pasture or wheat field the result is an area that generally reflects more sunlight, since crops and grassland are usually less absorbing than trees. The same is true when nomadic tribesmen allow their cattle or (especially) goats to overgraze on marginal land, since the destruction of vegetation markedly increases the reflectivity of the surface (SMIC, 1971; Glantz and Parton, 1975; Eckholm, 1975; Bryson and Baerreis, 1967).

Such changes in the solar radiation absorbed by the surface must certainly have an effect on the heat balance and climate of a region, and influence its precipitation as well as its mean temperature (Otterman, 1974; Charney et al., 1975; Charney, GARP-16, App. 2.6, 1975). A secondary effect is very likely to be the increase in windblown soil and sand (discussed in Section 2.2.5), which also affects the radiation at the surface and the stability of the atmosphere above it (Bryson and Baerreis, 1967).

So far as we know, there has never been a comprehensive worldwide inventory of this kind of effect, though we do know that some regional surface changes have been and will be very extensive (SMIC, 1971; Newell, 1971; Bryson, 1974). Flohn (GARP-16, App. 1.2, 1975) has made global estimates of some parts of the problem, such as the energy impact of the conversion of tropical rain forest to cropland and the effect of tropospheric dust due to vegetation destruction, and this appears to be a good start. While we do not know how much of a cumulative effect all these changes have had on our climate, our belief is that it has not been as extensive as some of the other effects that have been described.

2.3 Summary of mankind's influences on climate together with their time scales, and a comparison with nature

We have mentioned a number of anthropogenic causes for climate change in terms of their effects on the mean temperature of the surface, and Table 2 summarizes these effects. To a first approximation they can probably be considered as additive, because they represent small fractional changes (and therefore follow more or less linear relationships, though for much larger changes some of the effects must definitely become non-linear).

The last column of Table 2 indicates the expected rates of change of temperature, and we have presented them in order to make a comparison with the natural rates of change of temperature that would be expected based on the statistics of past changes. If an anthropogenic change is much smaller than natural fluctuations it is difficult--if not impossible with our current ignorance of the causes of such fluctuations--to distinguish it from the natural "noise." On the other hand, if it is larger than the expected natural fluctuations its "signal" should be fairly evident (Broecker, 1975; Mitchell, 1977).

A recent report by the U.S. National Academy of Sciences (NAS, 1975) contains a rough harmonic analysis of the mean temperature record of the past several hundred thousand years, and this is presented graphically in Figure 6. It can be seen that the long 100,000-yr period has a large amplitude (4°C) but produces a very gradual rate of change, with a maximum of only $\pm 0.0025^{\circ}\text{C decade}^{-1}$; and, on the other hand, the shorter 100- and 200-yr periods have small amplitudes (0.5°C) but produce relatively rapid rates of change, with maxima of ± 0.15 and $\pm 0.075^{\circ}\text{C decade}^{-1}$, respectively. In the decade of the 1970s the average natural rate of change is expected to be $-0.154^{\circ}\text{C decade}^{-1}$. According to this analysis the rate of change cannot be more than $\pm 0.257^{\circ}\text{C decade}^{-1}$.

There are a number of potential pitfalls in applying this kind of statistic, the main ones being (a) the assumption that there are such harmonics in the paleoclimatic record when it is only of finite length (which is borne out by the plethora of "discoveries" of other periodicities in other climatic records coupled with the suspicion that they cannot all be real (e.g., Aaby, 1976)), (b) the uneasy realization that we have no good explanation of any but the longer periods (which are in rough agreement with the Milankovitch (1930) hypothesis relating climate change to regular modulations of the earth's spin axis and orbit around the sun), and (c) the rather clear evidence that there have been sudden anomalies in the climate (always, it seems, in the direction of a very rapid cooling).

The last point is borne out in the upper part of Figure 6, which shows a particular record obtained by Nichols (1974; 1975), based on studies of ancient pollens in peat deposits at six locations across northern Canada, the dating being done by ^{14}C . From pollen counts one can derive the relative abundances of various kinds of shrubs, grasses, lichens, and trees, and this in turn indicates the position of the tree line and the mean

Table 2

Summary of Anthropogenic Influences
on the Global Mean Surface Temperature

Effect of Mankind	Time Period for the Effect to Occur	Influence on Surface Temperature (°C)	Rate of Change Toward the End of the Time Period (°C/decade)
Raising the carbon dioxide content of the atmosphere.	+25% by 2000 AD	+0.5 to 2 ^a	0.2 to 0.8
	+100 by 2050 AD	+1.5 to 6 ^a	0.3 to 1.2
Adding chloro-fluorocarbons to the troposphere.	0.8 ppbv by 2000 AD ^b	0.1 to 0.4 ^d	0.04 to 0.2
	2.5 ppbv by 2050 AD ^b	0.25 to 1 ^d	0.02 to 0.1
	3.5 ppbv by 2000 AD ^c	0.4 to 1.5 ^d	0.2 to 0.8
Raising the nitrous oxide content of the atmosphere.	+100% to 2050 AD	0.25 to 1 ^e	0.02 to 0.1
Adding aerosols to lower troposphere.	?	Heating ^f	?
Direct addition of heat.	50-fold increase by 2100 AD	0.5 to 2	0.05 to 0.2 ^g
Patterns of land use.	?	?	?

a. See Table 1.

b. Assuming continued FC production at 1973 level (NAS, 1976).

c. Assuming a 10% per year increase in FC production rate (NAS, 1976).

d. Estimate by Ramanathan (1975), and reviewed and extended by NAS (1976).

e. Estimated by Yung et al. (1976). This now appears to be an upper limit on the possible increase of N₂O in this time period.

f. It is not clear whether the upward trend in anthropogenic aerosols will continue-- it will depend to a large extent on control of sulphur-dioxide emissions, which will probably have to be reduced in some areas.

g. Estimated under the assumption that energy production would continue to grow as the product of the two central curves in Figure 2. In this case the total effect (about 1°C) would be more significant than the rate of change because it builds up over a fairly long period.

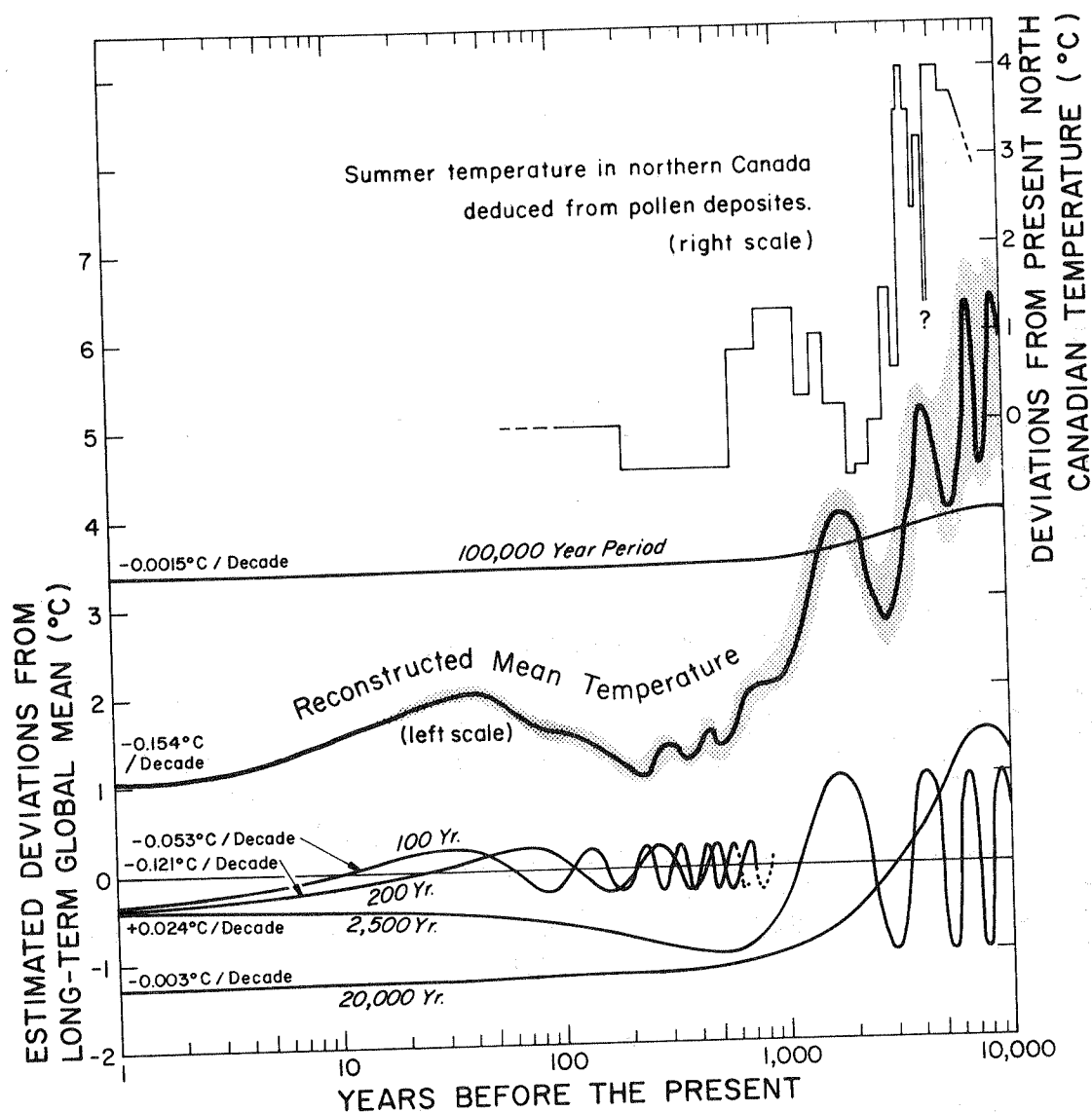


Figure 6. A review of the mean surface temperature changes during the past 10,000 years (lower part, left-hand scale). This is intended to show the general features of the changes; the five periodic functions (with periods from 100 to 100,000 years) from which the mean temperature was reconstructed were derived from a wide variety of paleoclimatic records (NAS, 1975), no one of which can be considered as entirely representative. It will be noted that the shorter-period fluctuations largely account for the rate of change (noted at the left end of each curve), while the longest-period fluctuation has the largest amplitude and largely accounts for the major alternations between the ice ages and interglacials. The temperature record for northern Canada (upper part, right-hand scale), obtained by Nichols (1974; 1975) from studies of pollen in lake sediments, is roughly representative of records obtained elsewhere at middle-to-high latitudes. Dating of such records is generally done by carbon-14 analysis.

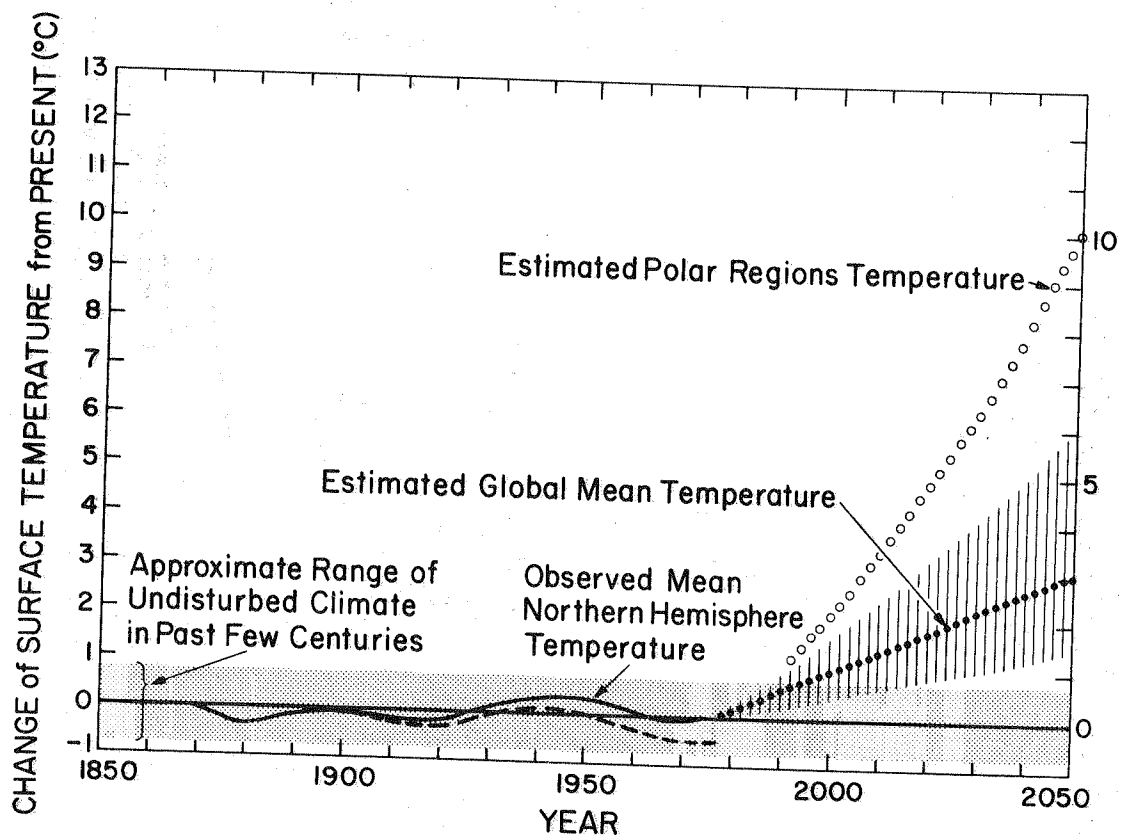


Figure 7. The mean surface temperature record for the northern hemisphere since 1860 (solid line), and what it might have been without the addition of carbon dioxide (dashed line). The shaded area includes almost the entire range of temperature fluctuations experienced during the past 1000 years or more. Future global mean temperature change (dotted line) is as shown in Table 3, the cross-hatching representing an uncertainty of a factor of two in the model calculations. Polar region temperature change is expected to be 3 to 5 times larger than the global mean. [Adapted from Mitchell (1977).]

summertime temperature or length of growing season (probably closely related). It does not tell much about wintertime conditions, however. The abrupt and short-term cooling at 4800 years ago (marked with a question mark in Figure 6, since it is not clear just how cold it got) killed off the spruce forests of northern Canada and forced the line separating forest from Arctic tundra southward almost to its present position. The tree line slowly moved back northward in the succeeding century or two, but then there was another less abrupt cooling around 3500 years ago, accompanied by an increase in forest fires in summer, that forced the tree line far south again.

This is just one example of this kind of climatic behavior, and there have been several others that were even more dramatic. For example, Flohn (GARP-16, App. 1.2, 1975) discusses one at 89,000 years ago that seems to have been worldwide and was probably considerably more intense. There is at present no general agreement on the causes of such short-term coolings, and in any case their timing is apparently random, so it would be folly to venture a guess as to when the next one might occur. All we can say is that it is highly improbable that one will occur in the next century or so, which is the period of our scenario, since these major events are generally spaced 10,000 to 20,000 years apart.

In summary, if we add the best estimates of each of the anthropogenic effects, with some judgment about the ones that are less likely to transpire, we conclude that the net influence of mankind is as shown in Table 3 and illustrated in Figure 7. We note from Table 2 that when we compare the rate of change of global mean surface temperature due to anthropogenic factors with the expected ± 0.1 to 0.2°C per decade natural changes they are significantly larger. The effect of adding carbon dioxide is the largest, and even the lower limit of that estimate is enough to cause a "signal" above the natural "noise" by the end of this century.

Table 3
Best Estimate of the Influence of
Mankind on Mean Surface Temperature

	Present	2000 AD	2050 AD
Absolute Change ($^{\circ}\text{C}$)	0.5	+1.2	+4
Rate of Change	0.15	+0.5	+0.7

- Assumptions:
- Manufacture of chlorofluorocarbons will remain at 1973 level.
 - Direct addition of heat will not be important globally until after 2050 AD.
 - Effects of aerosols and patterns of land use are not included.

Again the point must be emphasized that these all refer to the global mean surface temperature changes, and the corresponding changes at middle and high latitudes will be much larger, as shown in Figure 7. This distinction has important implications, as we will show in the next section.

3. IMPLICATIONS OF A WARMER EARTH

3.1 Length of growing season

One can quite simply make an empirical deduction about the relationship between summertime mean surface temperature and length of growing season by plotting them both as a function of latitude. It turns out that at middle and moderately high latitudes they are roughly parallel each other, and a good approximation is that a 1°C change in mean surface temperature in summer at a given latitude corresponds to 10 days change in growing season. The correspondence between length of growing season and yearly average temperatures is not quite as close, since wintertime temperatures are so strongly affected by continentality and regional differences, but the above rule of thumb still applies moderately well.

This being the case, an increase in global mean surface temperature of 1°C , for example, may result in about $+2^{\circ}\text{C}$ at 60° latitude and $+3^{\circ}\text{C}$ at 70° latitude, and this would give respectively about 20 or 30 days longer average growing seasons at these two latitudes. At 50° latitude the corresponding increase might be 15 days. This is the magnitude of the change that we estimate will occur a little before 2000 AD (see Table 3). (We have based this latitudinal dependence of temperature change on the model results of Manabe and Wetherald (1975) and Sellers (1974).)

3.2 Lessons from history

3.2.1 The temperature record

We have already mentioned the fact that there have been periods in the history of the earth when it was warmer than the present. In fact, when we study the paleoclimatic record on the time scale familiar to geologists we find that since the beginning of the Cambrian Period (about 500 million years ago) there have been just two relatively "short" periods when the earth had permanent ice at the poles, and the remaining 85 to 90 percent of that time the earth had virtually ice-free poles. On that time scale, then, we are now in an anomalously cold period (SMIC, 1971; Lamb, 1972).

A great deal of speculation has taken place about the reason for our present long-term ice age, and the most likely contenders are long-term solar fluctuations and continental drift--the latter being probably the preferred one currently. However, these extremely slow processes of climate change, whatever they are, seem largely irrelevant to our discussion of what may happen in the next century.

It is certainly pertinent, on the other hand, to enquire about the last few hundred thousand years, because that record is now becoming much clearer, and because there are some lessons here that may give helpful clues about the future.

Many readers of this report will recall the rather disturbing question that was raised in 1971 by a distinguished group of paleoclimatologists contemplating the climatic record for the Quaternary (the past one to two million years), a question that found its way into the public press and excited an investigation by the United States' White House (Kukla, et al., 1972). Their thought was, in brief, that in the past there have been fairly regular transitions about every 100,000 years between warm interglacials and glacial periods, that the interglacials have been relatively short and usually less than 10,000 years, that the end of the last warm interglacial (the Sangamon or Eemian, for which the record is clearest) occurred rather suddenly, and, finally, that we have enjoyed our present interglacial (the Holocene) for at least 10,000 years. So it was entirely reasonable to raise the question: Are we about to start our descent into another colder glacial period?

A subsequent sober review of this matter (Mitchell, 1972; NAS, 1975) has dispelled the fear that we are due for a "snowblitz," although this spectre has been kept alive by some popular writers (e.g., Calder, 1974). The probability of a large natural change in the next few centuries is very slight indeed, as can be seen by extending the sinusoidal curves of Figure 6 into the future--a point which was made earlier in Section 2.3.

3.2.2 The precipitation record

Most of the discussion so far has concerned the surface temperature and the effects that mankind might have on it, but it is equally important to know what might happen to the distribution of precipitation. In fact, it is the latter that largely determines whether vegetation will thrive and whether a region can grow food.

Even more so than temperature, precipitation is a function of the large-scale circulation patterns that can bring water vapor to a region, together with the regional factors that determine whether it will rain or snow. There must be a relationship between these all-important circulation patterns and the large-scale heat balance (or mean equator-to-pole temperature gradient), of course, since they are both measures of the activity of the atmospheric heat engine. The first is, in general terms, a measure of the kinetic energy of the system, and the other is a measure of the thermal energy available to run it. We would like to know more about this relationship.

It is natural to turn to our general circulation models (GCMs) and there have been a number of experiments with GCMs (some of them already referred to) in which changes in the heating applied to the system by the sun have been introduced, and the resulting change in the circulation pattern noted (e.g., Wetherald and Manabe, 1975). In a similar category, a number of other experiments have been done in which the surface boundary conditions of the last ice age, roughly 18,000 years ago, have been introduced into the computation (e.g., Williams *et al.*, 1974; CLIMAP, 1976). Unfortunately, we can no longer go back to that period and verify how well the model has reproduced the ice age climate.

Such experiments have been most instructive, but we must recognize that there are limits to the ability of a GCM to simulate reality, particularly where the subtle variations of seasonal precipitation patterns are concerned (Manabe and Holloway, 1975; Gates, 1975). In a very real sense, it is these precipitation patterns that determine where the deserts, marginal lands, and "food baskets" will be, and that is what should concern us in a world where the climate may be changing.

In spite of their limitations, our GCM experiments have shown dramatically that when there is a change in the heat input to the system the model atmosphere responds in a most complex way. For example, with an increase in the total heat supplied to the system there is an overall warming of mean surface temperature, but some regions will warm very much more than others, and there may even be a cooling in some places (Washington, 1972). The real atmosphere behaves the same way (van Loon and Williams, 1976a; 1976b). The same complex response undoubtedly refers to the patterns of precipitation, and we would expect that there will be places where the precipitation will increase and others where it will decrease in the course of any marked climate change.

Another way to find out what a warmer earth might be like is to study a time when the earth itself was warmer than it is now. Such a time actually existed roughly 4000 to 8000 years ago, during the period known as the "altithermal" (also known as the Hypsithermal, Atlantic, or Climatic Optimum--optimum for whom?), and paleoclimatologists are beginning to piece together the strikingly complex picture of the conditions that existed then, at the dawn of civilization. This warming is clearly shown in Figure 6.

Evidence for the conditions at that time is derived from the distribution of fossil organisms in ocean sediments and of pollens in lake sediments, the history of the amounts of water in lakes, the extent of mountain glaciers, the distribution of trees and other

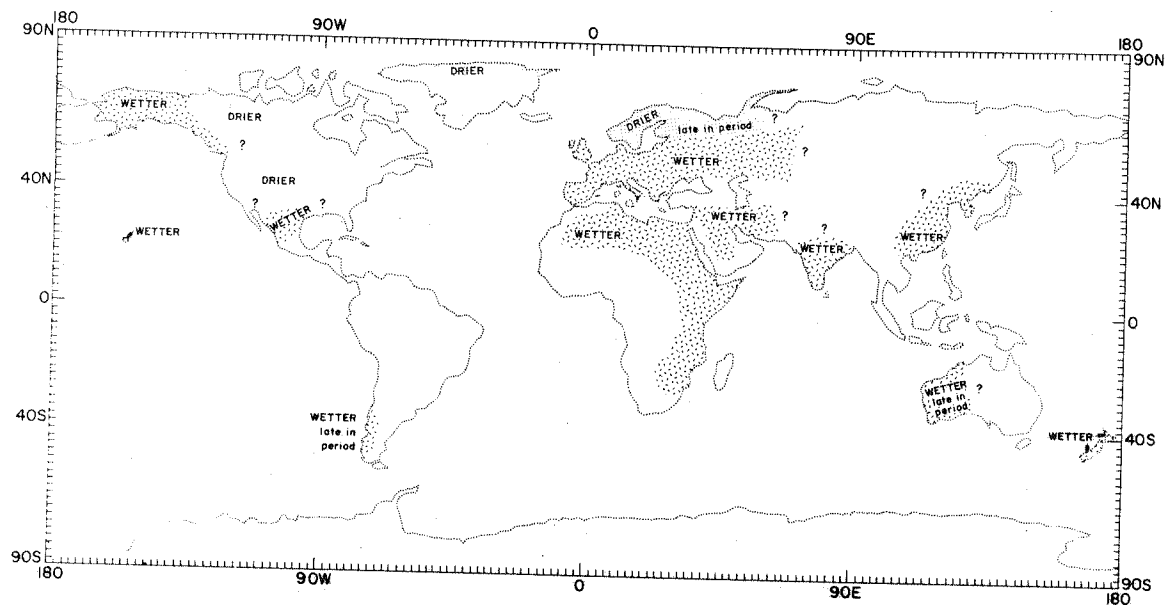


Figure 8. A somewhat schematic map of the distribution of rainfall, predominantly during the summer, during the Altithermal Period of 4,000 to 8,000 years ago when the world was generally several degrees warmer than now. The terms "wetter" and "drier" are relative to the present. Blank areas are not necessarily regions of no rainfall change--our information is still far from complete, and work is under way to fill in some of those areas.

vegetation in swamps, widths of tree rings, the location of ancient sand dunes, changes in the isotopic ratios of certain elements in ice and sedimentary cores, and so forth (Lamb, 1972; 1974; Flohn, GARP-16, App. 1.2, 1975; Kutzbach, GARP-16, App. 1.3, 1975). Out of many such investigations the picture of the conditions during the Altithermal period can be pieced together, as shown in Figure 8 referring to the precipitation relative to the present (Kellogg, 1977a; 1977b). It will be noted, for example, that North Africa was generally more favorable for agriculture than it is now, that Europe was wetter, Scandinavia dryer, and a belt of grass lands (sometimes called "the Prairie Peninsula") extended across North America, the eastern part of which subsequently became forested land.

We must caution the reader not to accept this as a literal representation of what might occur if the earth becomes warm again, since the causes and the characteristics of the warming 4000 to 8000 years ago could have been quite different from the characteristics of society's future effects. While we do not really know what caused that high level of mean temperature to be maintained during the Altithermal, one likely cause is the total output from the sun, and another possibility is the seasonal distribution of sunlight between the northern hemisphere and the southern hemisphere as the earth's elliptical orbit around the sun changed (the Milankovitch hypothesis). It is even possible that there was more carbon dioxide then, though we have no good evidence for this. In any case, each of these mechanisms to account for the higher mean temperature would presumably result in a different distribution of that heat energy, and therefore the patterns of the general circulation and precipitation would also depend on the mechanism involved.

Another reason for caution in using the Altithermal Period as a model for the future is the short time scale involved in our scenario. While the Altithermal seems to have evolved over a period of a few thousand years the anticipated warming may occur over a few decades. There are many components of the climate system, as we have mentioned, that have built-in delays, one being the ocean circulations and temperatures, another being the response of our land areas. We have discussed the tendency for a desert to reinforce itself because of its high albedo (see Section 2.2.7), a kind of positive feedback; and this could mean that the subtropical deserts will (for a time at least) resist a tendency toward more rainfall. These are clearly points that require more study.

In spite of all these reservations, it seems reasonable to study the way the world was when it was warmer than it is now, and to note that this at least represents a likely pattern for the future warmer earth. Using the real earth as our model is at least as good as, and probably better than, the theoretical numerical models that we currently run on our computers.

The fact that the subtropical deserts were wetter during the Altithermal, as shown in Figure 8, has a reasonable explanation in terms of two factors which must have been in operation. First, a warmer atmosphere will cause more water to be evaporated from the oceans, and the hydrologic cycle will consequently be more intense and there will be more precipitation generally, a point that has been verified by GCM experiments (Manabe and Holloway, 1975). Secondly, there will be a weakened equator-to-pole temperature gradient, so the general atmospheric circulation, and the tropical Hadley circulation in particular, will be less vigorous. Since a major cause of the present subtropical deserts is the suppression of convection in those regions by the descending arm of the Hadley cell, a decrease in this circulation should allow more convective precipitation in this part of the subtropics. While such a relationship is very likely real, it must be only part of the total explanation.

3.3 The fate of the ice masses

We have pointed out above that the most probable change in the mean surface temperature is a warming, and that the greatest changes will be in the polar regions, above 50° or 60° latitude (see Figure 7). This would certainly have an effect on the extent of polar ice and snow.

There are five distinct regimes of ice and snow: underground permafrost; the winter snow cover on the land that melts in the summer; floating sea ice, or "pack ice," some of which now survives through the summer in both polar regions; mountain glaciers, that can occur at any latitude; and the great ice sheets of Greenland and the Antarctic, that have remained more or less intact for many millions of years. Each of these regimes of ice and snow should be considered separately when we estimate their response to a change in the mean temperature at high latitudes, and the two that are probably most important to consider in our scenario are the floating sea ice and the great ice sheets. For an excellent review of this subject, see Untersteiner's Appendix 7 in GARP-16 (1975).

3.3.1 Arctic Ocean ice pack

The floating sea ice in the Antarctic appears and nearly disappears each year, while in the Arctic Ocean there is always a substantial area of multi-year sea ice the year round. The contrast between the seasonal behavior of the two polar regions can be illustrated by the fact that the area of pack ice frozen each winter around the Antarctic Continent (and melted each summer) is larger than the area of the entire Arctic Ocean.

Referring to the Arctic Ocean specifically, the major question is how much of a warming would be required to remove the pack ice completely, and whether such a complete removal will mean that it will remain open and not freeze over again in winter. There are a number of reasons for arguing that it probably would tend to remain open once the ice pack had been melted, barring a major change in sea level (Ewing and Donn, 1956; Donn and Ewing, 1966; SMIC, 1971; Budyko, 1974; Fletcher, 1965; Kellogg, 1975a; 1975b).

For one thing, the Arctic Ocean would present a dark surface in summer compared to the highly reflecting ice pack that exists now, so, even with some low clouds covering the area, a great deal more solar energy would be absorbed by the system in summer. (However, relatively more energy would be lost in winter.) Another rather compelling reason for thinking that the Arctic Ocean would be harder to freeze over once the ice pack had been removed is based on the fact that there is currently a layer of relatively low-salinity water floating under the ice pack (to a depth of 10 to 30 m), and, since this relatively fresh water has a lower density than the normal salt water of the ocean, it produces a stable layer that inhibits mixing and exchange of heat between the surface layers and the warmer waters below (Aagaard and Coachman, 1975). With the ice pack removed wave action and surface currents would be expected to eliminate this thin stable upper layer. For both of these reasons, it seems likely that if and when the Arctic Ocean ice pack is removed as a result of a global warming the open freely mixing ocean will not freeze over again. On the other hand, Untersteiner (GARP-16, App. 7, 1975) injects a note of caution lest we jump too quickly to this conclusion.

So far there is no adequate combined atmosphere-ocean-sea ice model that can be used to estimate the response of Arctic sea ice to a global warming, though there have been some notable advances in this area (Maykut and Untersteiner, 1971; Budyko, 1974; Rothrock, 1975; Untersteiner, GARP-16, App. 7, 1975; Washington *et al.*, 1976). It must require a considerable warming to remove the ice, however, since evidence from Arctic Ocean sediments suggests that it has never been ice-free for the past million years or more. Furthermore, Budyko (1974) estimates, based on a relatively simple pack ice model, that at least a 4°C warming in summer would be required to eliminate it.

An open Arctic Ocean would, of course, allow a great deal more evaporation than the frozen Arctic Ocean, and this would presumably result in more rain in summer and snow in winter around its shores. What this would do to the mean snow cover on land, or to the size of the Greenland ice sheet, is still a matter of speculation, but it would certainly represent a major difference in the patterns of temperature and rainfall that exist now. Experiments with the two-layer Mintz-Arakawa GCM have been performed at the Rand Corporation (Santa Monica, California) to determine the effect on temperature and precipitation of an open Arctic Ocean (Fletcher *et al.*, 1973), and the result was a warmer temperature

at the edge of the ocean by 10°C, and an even larger increase in the central Arctic. These results are for a wintertime situation. The change in precipitation in that model simulation experiment does not seem to have been very significant, however, which is surprising.

3.3.2 Ice sheets of the Antarctic and Greenland

Turning to the ice sheets of Greenland and the Antarctic, their total volume is determined over a long time period by a balance between the snowfall on the tops and the melting, ablation, or breakoff at their edges. Also, the effect of intermittent "surges" of an ice sheet must be considered (Hughes, 1970; 1973; Flohn, 1975), since these are dynamic systems. It is not evident that a warming will necessarily result in the decrease in the size of these ice sheets, since a warmer atmosphere can also hold more moisture, and this in turn can result in more snow fall on their tops and a larger volume (a hypothesis proposed by Scott as early as 1905). There is apparently some inconclusive evidence that the East Antarctic ice sheet (which is by far the largest) shrank during the period of the last glaciation in the northern hemisphere and then slightly enlarged during the warming period (Denton *et al.*, 1971; Flohn, 1963; Lamb, 1972, p. 485), out of phase with the continental ice sheets of North America and Europe. (This was apparently not the case for the Greenland ice sheet, however.)

Each of these ice sheets should be considered separately in such a discussion, since their characteristics are very different. Greenland, with a total volume that corresponds to about 7 m of ocean water, is influenced by the Arctic Ocean and the other sources of moisture in the northern hemisphere. It receives considerably more snow than the Antarctic ice sheets, and its southern end extends well below the Arctic Circle. The East Antarctic ice sheet is by far the most massive in the world, with a volume 8 to 10 times greater than that of the Greenland ice sheet (thus representing as much as 70 m of ocean), and its highest point is not far from the South Pole. The West Antarctic ice sheet, with a slightly smaller volume than that of the Greenland ice sheet, has less snowfall to replenish it, and unlike the other ice sheets its edges are partly grounded below sea level. There are already some signs of a current retreat of this ice sheet (Denton *et al.*, 1971), and, if there is a major warming and it retreats so that the Antarctic Ocean water can flow under it, it would presumably begin to melt faster (Hughes, 1973; Mercer, 1968). On a geological time scale it is this ice sheet that we should watch with some concern. However, obviously one should not expect much action in the time scale of human affairs--that is, for the next few centuries at least--since the time required for a turnover of water substance in the major ice sheets is on the order of 10^4 to 10^5 years (Untersteiner, GARP-16, App. 7, 1975).

It must be clear, however, that, considering the immense volumes of these three ice sheets, even a relatively small fractional change of their volumes would affect mean sea level. Since the turn of the century sea level has risen about 20 cm (SMIC, 1971), but this rate of rise has slowed since 1940 (Hicks and Crosby, 1975). Can this have been due to some melting of the ice sheets? Or can it have been caused by mankind's pumping of "fossil water" from underground aquifers?

In the glaciological literature there is a type of event that has attracted much attention, known as a glacier "surge." It is well known that mountain glaciers under certain circumstances can move very rapidly for a period of a few months or years, and then more slowly again. An explanation is that melting at the bottom of a glacier allows it to slide with less friction over the underlying rock, and the greater motion (once a surge starts) helps to generate heat at the interface, and that in turn maintains the motion until a new equilibrium distribution of mass is attained. The same could, in principle, happen to the ice sheets of the Antarctic (Wilson, 1969; Hughes, 1970) with very pronounced effects on the climate of the world as these great blocks of ice were carried to other latitudes by the ocean currents (Flohn, 1975; GARP-16, App. 1.2, 1975).

When conditions are warmer there is more likely to be water on the underside of an ordinary glacier, so an ice sheet might also be expected to respond to a warming by moving faster. Actually, in the case of the ice sheets, changes in the air temperature on the time scale in which we have been dealing would probably not be felt at the bottom, since conductivity in these ice sheets is poor and they are extremely massive. Therefore, it is highly unlikely, regardless of whether such Antarctic ice surges could occur or have occurred in the distant past, that they would be a part of our scenario of warming in the next century or so--but neither can we completely exclude it as a kind of highly unlikely event that might take place anyway.

4. VALUE OF A LONG-RANGE CLIMATE FORECAST

4.1 Who can use a climate forecast?

The scenario developed in this report (see Tables 2 and 3, and Figures 3 and 7) covers a time period that is comparable to the life of a human individual, and perhaps roughly comparable to the average turnover time of the buildings and factories of a large city, but very short compared to geological processes. Yet in planning for the future the time scale usually considered by a government policy maker has tended to be his or her expected term of office--though this appears to be changing.

Thus, even if scientists could agree that the future course of the climate would indeed more or less follow our scenario, there remains the question of how useful this information would be. Who would take advantage of it in their planning? What kinds of human activities would benefit from the knowledge that in the next few decades the temperature and precipitation patterns would be different?

The fact is that never in the history of mankind's affairs have planners and decision makers been given such a forewarning--with the possible exception of the Biblical story of Joseph's advice to the Pharaoh about the seven years of plenty and the seven years of famine. We have no experience with how to act, given several decades of lead time. Perhaps harbor designs and construction practices would be different if we knew sea level would rise, perhaps real estate values in marginal regions would be affected if we knew the growing conditions would improve, perhaps new orchards would be planted with the sure prospect of a warmer earth, and so forth. However, so far these situations are hypothetical, until scientists can give more assurance than they seem to feel they can give at present (Kellogg and Schneider, 1974; Schneider, 1976).

It may never be possible to speak with complete assurance about the future of the climate, because (as we have emphasized before) there will inevitably be natural climate fluctuations [perhaps caused by volcanic activity or changes in the sun (Roberts and Olson, 1973; Wilcox, 1975)], longer-term climate changes, and sudden anomalous cooling events of the sort that have occurred in the past. Until we know a great deal more than we do now about the climate system and the external influences on it we will not be able to predict these natural interventions.

The fact remains, however, that our best estimate of the future magnitude of mankind's effects, based on a prediction of the second kind, is that these effects will be considerably larger than the expected natural changes. Therefore, it seems that the warming will be likely to dominate throughout the next century or more, and the probability of a natural cooling taking over is low. This should be a useful piece of information if we can agree on it.

There is another aspect to this prospect that makes it even more unique: If we wanted to badly enough we could take action to avoid it. It may turn out that the extreme warming that could conceivably occur toward the latter part of the next century will be deemed "unacceptable" by the nations of the world, and that strong international action

will then be taken to drastically cut down the burning of fossil fuels or to institute countermeasures against the warming. These are certainly options that must be kept in mind.

4.2 The longer time scale

The magnitude of such natural interventions is expected to be larger when we consider a period longer than that of our scenario. Figure 6 shows that the amplitudes of the 100,000, 20,000 and 2,500 year oscillations are larger than the 100 and 200 year oscillations; and another way of expressing the same general concept (used by those who dislike harmonic analyses) is to speak of climate as an almost stochastic process producing random fluctuations with extra spectral power in the longer periods, or a "reddened spectrum" (Kutzbach and Bryson, 1974; NAS, 1975). If some of the periodic oscillations prove to be real (as they probably are) there is a chance that we can make some long range predictions of the natural climate changes, but to the extent that it is a random or stochastic process predictions can only be in probabilistic terms (Mitchell, 1976).

As we look at the longer range, then, beyond 2050 AD and the end of this scenario, we may be faced with larger natural changes, but it is also possible that mankind's influence will continue to grow larger. In the short term the largest single effect is due to our addition of carbon dioxide (see Table 2), and the continuation of this activity could result in a further increase beyond 2050 AD if coal continued to be burned. Furthermore, recall that the estimated relaxation time for this added carbon dioxide, the time required for the deep ocean to take up about two-thirds of it, is estimated to be 1500 years. Thus, the carbon dioxide released in the next century or two will remain with us in the atmosphere for the next millenium.

It may be somewhat fruitless to consider the centuries ahead, partly because of our inability to predict what nature may have in store, but largely because we do not know what mankind will do. It is possible to imagine a technologically successful and vigorous "post-industrial society" with ample food and energy resources, a stable population, and a continuingly increasing warming effect on the planet; and it is also possible to imagine a society that is exhausting the earth's natural resources and being forced into a declining population and a declining standard of living. There are prophets of each of these alternative fates for civilization (see Section 1.3). The future choice will probably not lie with technology itself, but in the skill with which technology is used and the social structures that are adopted (Kellogg and Schneider, 1974; Schneider, 1976; Kahn *et al.*, 1976).

We mention these matters to indicate the nature of the problems that one must face as one looks at the more distant future. Will climate change pose an ultimate limit to human growth? This seems unlikely, but we cannot be sure of the answer. The only thing that is abundantly clear is that scientists, technologists, and the leaders of society must work together to make the right choices in the face of uncertainty. The dialogue between them has already begun.

5. NARROWING AREAS OF UNCERTAINTY

Scientific endeavor is often seen as an almost random process of poking into shadowy corners to retrieve new morsels of knowledge. While these morsels often prove to be valuable, there are situations where science faces a set of relatively well formulated problems, and then the process of selecting which dark corners to penetrate need no longer be random. When the answers to these problems will have an influence on the future course of mankind, then scientists have little choice but to try to bend their efforts together.

The future effects of mankind on the climate seems to be a case in point. There are a number of problems that need to be solved before we can make a "prediction of the second kind" with the degree of certainty that is required by society. The question is one of narrowing those areas of uncertainty that are not only challenging scientifically but have the most important implications for our future--and the future of our children.

We will single out those problems that seem to be clear enough to attack now and which seem to be most demanding of an answer, fully realizing that research is hardly ever a thing that can be planned in detail ahead of time. Furthermore, the areas will be limited to those involving the effects of mankind, and we will not deal with the larger question of research on the physical basis of natural climate change. These are dealt with elsewhere (GARP-16, 1975; NAS, 1975).

5.1 Climate modeling

Predictions of the second kind depend on determining the response matrix of a climate model that includes as many of the important feedback loops of the climate system as possible, either explicitly or implicitly by parameterization. We may be able to satisfy ourselves that for certain purposes a set of feedback loops can be neglected in the model, but this requires careful study.

Great labor and ingenuity has gone into the development of a variety of climate models already (Schneider and Dickinson, 1974; GARP-16, 1975), but it is generally recognized that for climate experiments there are at least three parts of the system that must be included in our models better than they have been so far, so that their responses can be taken into account. These are:

- o response of cloudiness
- o response of ocean circulations
- o response of polar sea ice (to be discussed further).

In addition to improving our understanding of the components of the climate system, illustrated in Figure 1, a major effort must continue to be directed toward schemes for coupling them together. As our numerical techniques and the power of computers improve we should be able to build more complete coupled models with which to do more refined experiments on the climate system.

5.2 Carbon dioxide sources and sinks

Since the increase in carbon dioxide content of the atmosphere appears to be the largest single anthropogenic influence on climate now and to be expected in the next century, we must be sure we understand its natural sources and sinks. Its main reservoirs (outside of fossil fuel still in the earth) are the oceans and the biomass of the earth, mainly organic material in soils and the forests. The specific questions relating to carbon dioxide that have been only partially answered so far are these--and there are several ways of asking them:

- o how have the upper layers of the ocean taken up the added carbon dioxide from the atmosphere already? and what is the temperature dependence of the process?
- o where and how rapidly do these upper layers mix with the deep ocean water? and how will this exchange be influenced by a global warming?
- o what is the magnitude of the biomass sink? and how will it be affected by deforestation, especially in the tropics? and how will various ecosystems respond to a changed climate and an increased atmospheric carbon dioxide content?

5.3 Arctic ice pack

Of all the subsystems of the climate system, the one that is likely to play the most significant part in a warming of the earth is the Arctic Ocean ice pack, for reasons given in Section 3.3.1. The WMO Executive Committee has already noted this as a special area of study (in Resolution 12 (EC XXVIII)). If the ice pack is sensitive to warming, and if it were possible to remove it all, this would come as close to an "irreversible" process as anything else we can think of. The heat balance of the ice pack has been studied extensively (Fletcher, 1965; Untersteiner, GARP-16, App. 7, 1975), but it is still difficult to model (Maykut and Untersteiner, 1971; Washington *et al.*, 1976). The variable effect of open leads on heat transfer between surface and atmosphere, the lack of a good description of the mechanical or constitutive properties of sea ice, and the difficulty of assessing heat transfer in the upper ocean layers seem to be the main difficulties now, and there are others. The development of a better model of this ice pack would therefore seem to demand a very high priority.

5.4 Ice sheets

The possibility that a major global warming will cause a small fractional change in the volume of the ice sheets of the Antarctic and Greenland is very real, though we are not even sure of the sign of the change (see Section 3.3.2). Since together they account for enough water substance to increase sea level by 80 m, even a small and barely perceptible change in volume would slowly impact all the coastal cities and plains of the world. This could be among the most devastating and costly of all the environmental effects that we have discussed. In view of this, there are at least two major areas of investigation that should be pursued (in addition to continuing to monitor sea level):

- o improve the models of the ice sheets, including not only the internal dynamics of the ice mass but the relevant meteorological factors of temperature, precipitation, and atmospheric circulation as they will be affected by a global warming and changes in other parts of the system, e.g., in the case of Greenland a more open Arctic Ocean;
- o carefully monitor the topography of the ice sheets; and radar altimeters on satellites may now provide a new tool for obtaining unprecedented accuracy (less than 1 m) over relatively level parts of the ice sheets.

5.5 Changing patterns of temperature and precipitation

A global warming will be most noticed by those living in places that are affected by the largest changes in temperature and precipitation, and these parameters will certainly vary from region to region. It is therefore not enough to predict the overall response of the climate system, for we must try to foresee the regional changes. There are two approaches to this, as has been discussed (see Section 3.2.2):

- o experiment with changing the boundary conditions of improved general circulation models that include realistic topography and hydrologic processes;
- o clarify the picture of the Altithermal period, when conditions were warmer, on a region-by-region basis.

5.6 Aerosols

We have not been able to assign any numbers to the effects of anthropogenic aerosols on global or regional climate because of a lack of knowledge about the optical properties and geographical distributions of such aerosols. Furthermore, the character of anthropogenic aerosols must be changing as efforts are made to suppress the emission of the larger soot particles from power plants and mills, control the use of backyard incinerators, limit slash-and-burn agricultural practices, and so forth--all this combined with the continued increase of sulphate particles produced secondarily from burning coal and fuel oil (see Section 2.2.5). We must therefore study present aerosol types and also try to predict the course of future emissions.

Among the recommendations of an ad hoc Working Group on Aerosols and Climate that met in Garmisch Partenkirchen in August 1976, chaired by R. Charlson, were the following (with some additions):

- o agree on the methodology for describing aerosol characteristics, including their optical properties, in terms of a few fundamental aerosol types;
- o make measurements at selected locations and times to develop a simple aerosol climatology, showing the distribution seasonally, geographically, and with altitude of the fundamental aerosol types;
- o model the direct radiative effects of these aerosol types on the regional heat balance under both cloud-free and cloudy conditions, and determine the sensitivity of the overall results to variations of relevant measured or assumed parameters;
- o survey air pollution control activities and plans in major or representative countries to obtain an estimate of the trends that can be expected in the future.

5.7 Other areas of study

While these appear to us to be the problems that demand the most immediate attention in our present context, there are, of course, many others. The possible changes in stratospheric ozone, for example, have implications for the climate as well as for solar ultraviolet (Ramanathan et al., 1976); any increase in nitrous oxide and fluorocarbons in the troposphere increases surface temperature, and the nitrous oxide-fertilizer issue will not be settled until we know more about the oceans as a source; changes of the characteristics of the land will have an effect on heat and water balance, and this will influence regional climate; and so forth. Clearly, none of these factors can be said to be unimportant.

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