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Numerical Modeling Experiments

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PREFACE

This article was prepared for the Joint U.S. POLEX Panel to the U.S. Committee for the Global Atmospheric Research Program (GARP), and originally appeared as pp. 80-95 of the report: *U.S. Contribution to the Polar Experiment (POLEX), Part 1: POLEX-GARP (North)*, National Academy of Sciences, Washington, D.C., 1974. It is being reproduced here in order to increase its availability to the climatic research community and to the staff of the Rand Climate Program in particular.

Numerical Modeling Experiments

W. Lawrence Gates

D.1 INTRODUCTION AND SCIENTIFIC RATIONALE

The polar regions of the earth are generally regions of net radiative energy deficit and maintain their climatic equilibrium by the receipt of energy transported from lower latitudes. They are therefore an important part of the overall pattern of thermal forcing of the atmosphere and ocean, and variations in their thermal equilibrium may be expected to affect the character of the global circulation.

By the same token, however, the climate of the polar regions is itself largely determined by the global circulation pattern, and it is therefore difficult to separate the polar atmosphere from the remainder of the atmosphere. We, therefore, envision a hierarchy of numerical experiments, culminating in the design of improved global numerical models in which the role of the polar regions may be made clear. It is believed that numerical models offer the best possibility for such a quest, since they consider a broad range of interacting dynamical effects and permit flexibility in parameterization.

Of the many physical processes represented in the more general atmospheric and oceanic circulation models, one is of particular importance in the polar regions: *the surface heat balance*. Each of the component processes of the surface heat balance (such as the behavior of sea ice, the surface-sensible heat flux, and the cloudiness) plays an important role and should be given special consideration in the design of numerical modeling experiments related to polar climate (see Figure B-4).

It is felt that the primary function of numerical modeling experiments at this time should be to establish the general distribution and characteristic variability of the physical processes in the polar heat balance. Systematic experiments directed to this end will serve to document the need for both new observations and improved parameterizations. Such a program would utilize the significant skills and interests of the U.S. numerical modeling community as a part of POLEX and would foster new research directly related to the problem of climate.

It is recognized that the general problem of the physical basis of global climate is being considered by the Panel on Climatic Variation of the USC-GARP, of which a preliminary subpanel report has been prepared for the time scales of concern to POLEX (USC-GARP draft report, Group 1). The present report will, therefore, confine its attention to the design and interpretation of numerical modeling experiments that illuminate those physical processes important in the arctic regions. The corresponding antarctic problems will be considered in later reports concerning POLEX-South.

D.2 MODEL PARAMETERIZATION REVIEW

As a first step toward the successful numerical modeling of polar climate, the various physical parameterizations made in numerical general circulation models need critical review and testing for arctic conditions. This need also has been cited by the GARP Joint Planning Staff [1973] Working Group on Numerical Experimentation, Joint GARP Organizing Committee. The model formulations for sensible heat flux, evaporation, and cloudiness particularly need to be reviewed and the resultant simulations compared with observation. Means should also be sought to introduce some measure of ice and soil morphology into the models, and the parameterization of leads in the Arctic pack ice is of particular importance.

The numerical procedures used in these models for the polar regions also need review, especially the resolution and stability near the poles. The horizontal grid may require refinement to resolve important smaller-scale processes in the Arctic (such as the sea-ice boundary and orographic winds). Most numerical general circulation models employ special computational procedures at high latitudes in order to ensure the solution's smoothness, but the polar rotational singularity poses a continuing numerical problem [Shuman, 1970].

D.2.1 Atmospheric General Circulation Models

The several global atmospheric numerical models differ in their vertical resolution, in the methods of numerical solution, and in the details of the physical parameterizations. All, however, treat the all-important surface heat balance in much the same way. It is therefore useful to review briefly their treatment of the basic processes involved.

D.2.1.1 SENSIBLE HEAT FLUX

Of particular importance in the Arctic is the vertical turbulent flux of sensible heat from the surface. This is modeled by one form or another of the bulk transfer formula

$$\Gamma = \rho C_p C_D |\vec{V}_a| (T_s - T_a), \tag{D1}$$

where ρ is the surface air density, C_p the air's specific heat at constant pressure, C_D the drag coefficient (itself sometimes dependent on wind speed and terrain), $\vec{V}_a$ the surface wind velocity (at anemometer level), T_s the temperature of the earth's surface (whether water, ice, or bare land), and T_a the near-surface air temperature.

During the arctic winter the sensible heat flux over ice- and snow-covered areas is predominantly downward, that is, toward the radiatively cooled surface whose temperature is generally lower than that of the overlying air. This flux may be spectacularly reversed over open water areas, however, where an upward flux 100 times larger may occur [Badgley, 1966]. Even a small amount of open water can therefore dominate the surface heat balance, and it is for this reason that the presence of even relatively small leads or polynyas in the arctic ice pack is of such importance.

D.2.1.2 EVAPORATION

Over a uniform surface the evaporation rate or moisture flux E is modeled by a formula of the type

$$E = \rho C_D |\vec{V}_a| (q_s - q_a), \tag{D2}$$

where q_s and q_a are the surface and near-surface mixing ratios, respectively, with q_s taken as the saturation value at T_s over a water surface. Since the surface temperature of ice is restricted to be at or below the melting point, q_s over ice assumes the saturation value of 0 °C during the warmer months; this provides an important moisture source for evaporation. The largest evaporation occurs over the open-water areas in the Arctic, along with the large upward sensible heat flux noted earlier.

D.2.1.3 CLOUDINESS

The presence of clouds is associated with the occurrence of condensation in the atmospheric models. Cloudiness at a particular grid point is introduced when saturation is predicted as a result of either large-scale moisture flux convergence or vertical convective adjustment. In most models such clouds are assigned at the lower, middle, or upper levels of the model's troposphere and affect the computed radiation balance through their assumed albedo, cloud top, cloud thickness, and liquid-water content.

In some general circulation models the local fractional convective cloud amounts are taken proportional to the local relative humidity, while in others they are assigned as complete overcast. The simulated clouds are allowed to modify the fluxes of shortwave and long-wave radiation through both reflection and absorption (although in some models the climatological cloudiness is used for this purpose). In all general circulation models, the occurrence of clouds is a by-product of the occurrence of precipitation to evaporate. None of the models allows clouds themselves to be advected horizontally, and none makes provision for the occurrence of large-scale nonprecipitating clouds, especially of the stratus variety. These features impose serious limitations in the numerical models' simulation of arctic cloudiness and clearly require further attention.

D.2.1.4 SURFACE HEAT BALANCE

We may write the net heat flux at the earth's surface as

$$(1-\alpha)S - R - \Gamma + C - LE - L_f M, \tag{D3}$$

where α is the surface albedo, S the shortwave radiation incident at the surface, R the net long-wave radiation flux leaving the surface, C the conduction of heat from beneath, and M the rate of melting of surface snow or ice. Here Γ and E are the sensible heat flux and evaporation as discussed above, and L and L_f are the latent heats of vaporization and fusion, respectively.

Over bare land (and over ice- or snow-covered land surfaces) the surface temperature T_s is presently determined in all general circulation models by the requirement that the expression (D3) be equal to zero. Most models assume in addition that there is no heat conduction from or into the ground ($C = 0$), and in the absence of melting snow, the term $M = 0$ also. In models in which snowfall is accumulated on the ground, the surface albedo α is varied according to the local snow depth; in other models the albedo is an assigned function of season and latitude only.

The surface temperature over arctic sea ice is determined from expression (D3) set equal to zero, with some provision made for heat conduction through the pack ice of the form $C = K/h(T_f - T_s)$, where K is the thermal conductivity of sea ice, h the assigned ice thickness (usually taken to be 2 m), and T_f the freezing point of seawater beneath the ice. The ice's surface temperature, however, is not allowed to rise above the melting point. Over open water the ocean's surface temperature (T_s) is prescribed in uncoupled numerical models of the atmospheric general circulation. The surface heat balance (D3) is therefore here disregarded, although local evaporation and sensible heat flux are computed as above.

A number of alternative flux and boundary-layer parameterizations have been tested in short-range predictions with atmospheric circulation models [Delsol *et al.*, 1971], but their climatic conseqeunces have not yet been explored. A systematic review of the adequacy of the widely used bulk transfer formulas over the Arctic is very much in order.

D.2.2 Oceanic Circulation Models

In general, numerical models of the ocean circulation are somewhat less developed than their atmospheric counterparts. The wind-driven and thermohaline circulations in an idealized basin have been calculated in response to prescribed surface momentum and heat fluxes in a number of models of uniform depth [Bryan and Cox, 1968], and such calculations have recently been extended to the world ocean [Takano *et al.*, 1973]. Only one baroclinic ocean model, however, has included a realistic lateral and bottom configuration for the Arctic Ocean [Cox, 1974]. Even in this solution, however, the heat and mass fluxes into and out of the Arctic Basin are not well simulated, and the role of salinity in stabilizing the arctic surface waters is also not adequately represented.

Of perhaps greater importance, however, is the ocean models' lack of an effective modeling of the floating arctic pack ice. In the most recent attempt to model dynamically the ice thickness [Bryan, 1969], the all-important formation of leads was neglected, as was the advection of the thicker ice itself. The effective modeling of these processes requires a constitutive relation for pack ice under external (wind, water) and internal (ice) stress. Development of such relationships is a major aim of AIDJEX [Maykut *et al.*, 1972].

As a complement to oceanic circulation models, consideration should be given to the formulation of one-dimensional models of the surface mixed layer. In such models the time variations of the local depth of the mixed layer are calculated in response to wind-induced stirring and the local surface heat balance. Although they neglect the horizontal transport processes, such models can simulate the day-to-day variations of the local mixed layer in stratified water [Denman and Miyake, 1973].

D.2.3 Coupled Atmosphere/Ocean Models

Only a solitary calculation has been made in which atmospheric and oceanic circulation models have been dynamically coupled [Manabe and Bryan, 1969]. In this case the atmosphere's surface wind stress was used to drive an idealized ocean (of uniform depth and rectangular sides) and the surface heat exchanged from one fluid to the other. The sea-surface temperature and the surface processes dependent on it are thus determined jointly by both the atmosphere and ocean. The preliminary results tend to confirm the widely held view that the oceans play an important role in the maintenance of global climate, particularly in the higher latitudes. Although such models have not yet been applied specifically to the Arctic, the development of suitably coupled global models is now under way at a number of institutions.

D.2.4 Steady-State Models

Although it is believed that the time-dependent global models discussed above offer the best dynamical framework for the investigation of climate-related physical processes in the Arctic (and for the identification of critical observations), some consideration should be given to the development of steady-state models for the coupled atmosphere–ocean–ice system. For example, the locations of both land and sea ice might be specific (as now done in the global models) and the resultant steady-state distribution of the surface temperature determined within the polar basin. From this, the various elements of the surface heat budget could then be estimated. Such a model might be a two-dimensional extension of the one-dimensional models developed by Sellers [1973] and Budyko [1969], for example.

It is recognized that the proper parameterization of time-dependent fluxes is a key problem in steady-state models, although it is perhaps less serious for the ocean than for the atmosphere. In view of the relatively small spatial variations of arctic sea ice and arctic ocean-surface temperatures (and the relatively low levels of atmospheric kinetic energy in the polar troposphere), such steady-state models might, in fact, be more successfully applied to the arctic region than to the lower latitudes. Some degree of polar axial symmetry might also be profitably employed.

D.3. MODEL PERFORMANCE REVIEW

As a second step toward the successful numerical modeling of arctic climate, the performance of the various present global circulation models should be

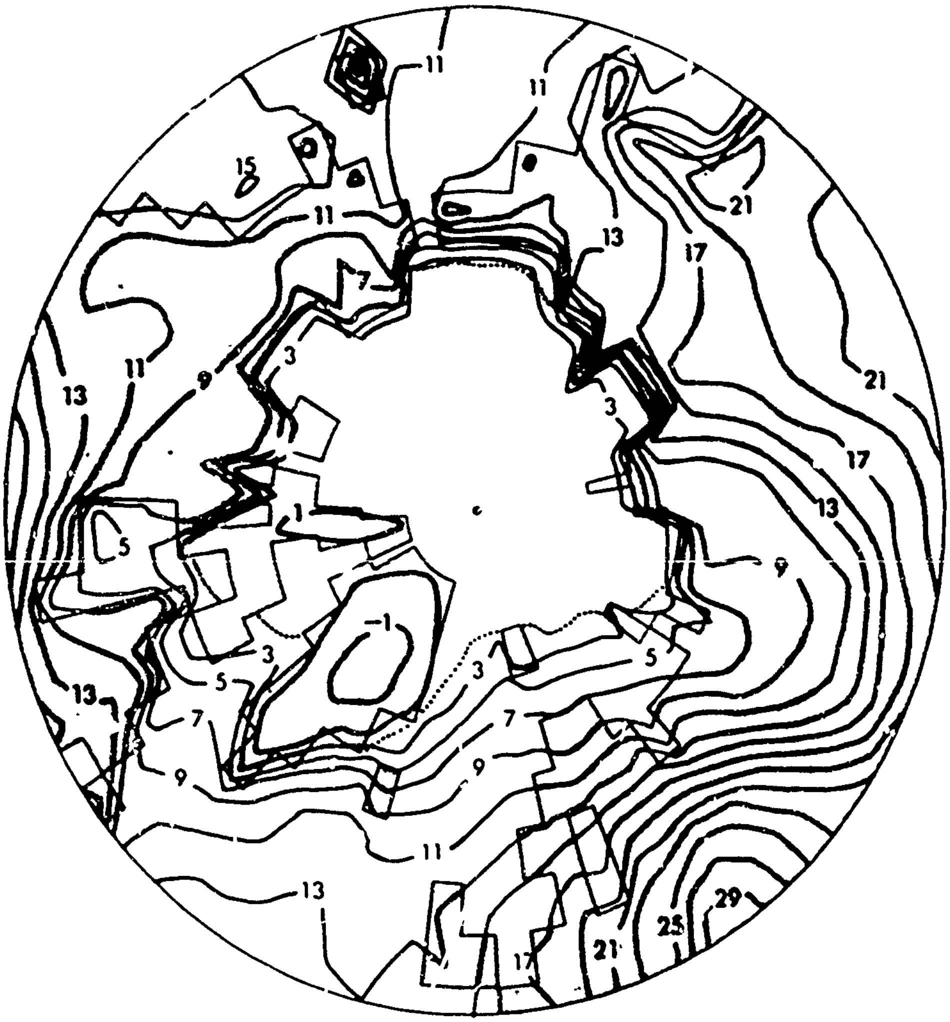

FIGURE D-1(a) The *simulated* July surface-air temperature from a two-level atmospheric model [from Gates, 1973] The isotherms are drawn every 2 °C, and the shading denotes land areas as resolved by the 4° latitude, 5° longitude numerical grid north of 50N The dotted line denotes the assigned limit of pack ice

specifically reviewed in the arctic region. In most model summaries the polar regions have recieved little attention, and the level of model fidelity in high latitudes is not well established. In particular, the ability of atmospheric models to simulate the seasonal regimes of the elements of the surface heat balance (including the sensible, latent, and conductive heat fluxes) and the related elements of precipitation, evaporation, and surface runoff needs systematic evaluation.

We may note, however, that for many of these climatic elements there are inadequate observational data against which to compare a numerical simulation. The observations for surface air temperature are perhaps the most

FIGURE D-1(b) The *observed* July surface-air temperature [from Schutz and Gates, 1971, 1972]. The isotherms are drawn every 2 °C, and the shading denotes land areas as resolved by the 4° latitude, 5° longitude tabulation grid north of 50N as in (a).

adequate and are compared with those of a representative atmospheric general circulation model [Gates, 1973] in Figures D-1 and D-2.

The simulated and observed surface air temperature is shown in Figure D-1 for July in the region north of 50°N. The large-scale air-temperature pattern may be considered reasonably satisfactory; in summer both the calculated and observed surface-air temperatures over the pack ice are between 1 and 3 °C, with the isotherms concentrated along the edge of the ice-covered Arctic Ocean. Closer examination, however, shows that the high temperatures over the interior of the surrounding continental areas are overestimated in Eurasia and underestimated in North America, by a few degrees Celsius in each case. The cold surface-air temperatures simulated over Greenland are apparently too high by about 10 °C

FIGURE D-2(a) The *simulated* January surface-air temperature. The isotherms are drawn every 4 °C [see Figure D-1(a)].

The corresponding comparison for winter is shown in Figure D-2, where again the large-scale patterns are similar. The coldest air is found over Siberia (and Greenland), where the simulated temperatures are too high by nearly 10 °C. It is over the arctic ice itself, however, where the errors are largest; in the Central Arctic the model's surface-air temperatures are some 10–15 °C too high, and there are errors of 5 °C over the Norwegian Sea. These errors illustrate the model's systematic underestimation of the low temperatures beneath the surface winter inversion.

This model's simulated cloudiness for the arctic summer shows a systematic underprediction of the observed cloudiness by about 50 percent sky coverage. Large amounts of low-level stratus clouds are typically observed in summer over the Central Arctic ice pack and are not adequately portrayed in the model. In winter the simulated total cloud amount compares more

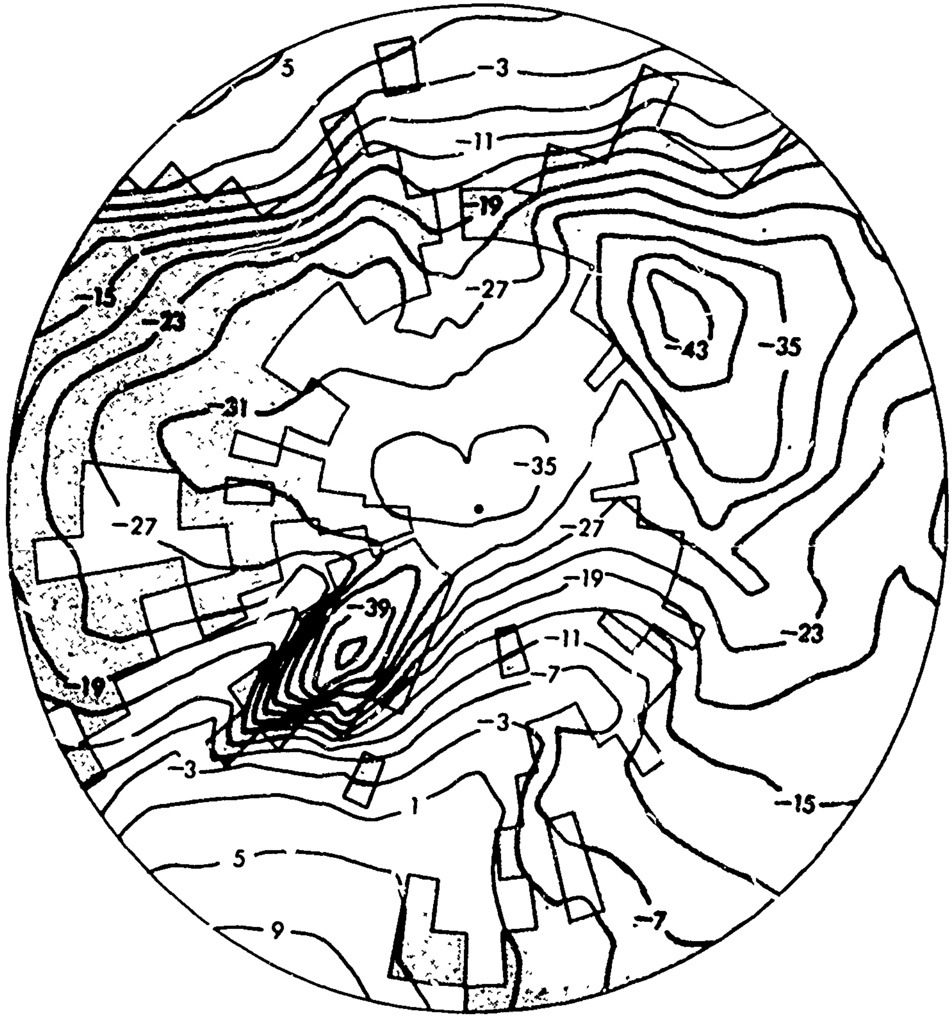

FIGURE D-2(b) The *observed* January surface-air temperature. The isotherms are drawn every 4 °C [see Figure D-1(b)].

favorably with observation but continues to show an underestimation. The maximum cloudiness is now found over the Norwegian Sea and is associated with the moisture flux from the adjacent open water.

Elements of the surface heat balance are also simulated by the atmospheric models and may be provisionally compared with the limited available data. In general, the simulated evaporation rates are of the order of 1 mm/day over the Arctic Basin in summer, which may be compared with the observed average values [Vowinckel and Orvig, 1970] of a few millimeters per day over arctic ice. In winter, the simulated evaporation rates are about 0.5 to 1 mm/day over the Arctic, which also compare favorably with available observations. The calculated precipitation over the arctic ice is also between 0.5 and 1 mm/day in both summer and winter and appears to be an overestimate of that observed in both seasons.

The model's simulated sensible heat flux over the pack ice is about -50 langleys/day in summer and even more negative in winter; the simulated net surface heat balance becomes positive only in summer. The limited observational data available [Vowinckel and Orvig, 1970] indicate that these values are too negative and are likely due to the model's inadequate representation of open water areas. This suggests that the few percent of open water estimated [Vowinckel and Orvig, 1970] for the polar ocean during most of the year probably has a major influence on both the sensible heat flux and the arctic surface heat budget, especially during winter.

A similar analysis of the elements of the arctic climate simulated by other global atmospheric models could be made, such as those of the National Center for Atmospheric Research [Kasahara and Washington, 1971], the Geophysical Fluid Dynamics Laboratory [Holloway and Manabe, 1971], or Goddard Institute for Space Studies [Somerville *et al.*, 1973]. The above summary is representative, however, and serves to illustrate such models' performance in the Arctic.

D GLOBAL NUMERICAL EXPERIMENTS

As a third step toward the successful modeling of arctic climate, a series of carefully designed numerical experiments should be made with presently available circulation models, in which the surface boundary conditions in the Arctic are specified in a particular manner. While such experiments should eventually be made with fully coupled atmosphere-ocean-ice models, valuable insight into the dynamics of arctic climate can be obtained from models of the separate media during the period of POLEX.

D.4.1 Atmospheric Models

Of particularly great interest would be an experiment of at least 12 months' duration with an atmospheric general circulation model in which the surface boundary condition was changed by the removal of all sea ice from the Arctic Ocean. Preliminary experiments of this sort have been made previously, but the question has not received definitive analysis with an extended integration. Even though the present atmospheric models do not permit either the formation or disappearance of sea ice during the course of an integration (and do not adequately represent the presence of leads), the comparison of a simulation with normal arctic ice and one with a completely ice-free Arctic Ocean would illuminate the mechanics of the two most widely contrasting arctic regimes thought possible. An analysis of the ice-free and normal cases would show the thermal control exerted by the ice pack and would also illuminate the role of the ice in the formation of polar air masses and in subpolar cyclogenesis.

A second numerical experiment of at least seasonal length with a global atmospheric model is suggested in which the surface sensible heat flux as determined by the model is modified to represent the presence of leads in the ice pack. Such an experiment would show the sensitivity of the arctic climate to the state of the ice cover and would permit a new examination of the components of the surface heat and moisture balances under a more realistic ice regime. This experiment, and the ice-free experiment suggested above, appear to be the most pertinent ones that could be conducted with prescribed ocean-surface temperature and sea ice for the Arctic.

D.4.2 Oceanic Models

Although models of the World Ocean circulation are less well developed than are those for the atmosphere, there are a number of numerical experiments that could shed light on the dynamics of arctic climate. The most obvious experiment is one in which the atmosphere surface heat flux and wind stress are fixed at climatological values and the consequent ocean circulation determined. This is, in fact, just the configuration used in present global oceanic experiments [Cox, 1974]. Variants of such an experiment are those in which the ocean density is specified climatologically and the currents calculated diagnostically [Marchuk *et al.*, 1973]; even here, however, the models have not yet been extended into the Arctic Ocean. In addition to the circulation within the Arctic Ocean, such experiments could simulate the heat transport into the Arctic under realistic mean conditions. According to the most recent estimate [Von der Haar and Oort, 1973], the oceans accomplish approximately 40 percent of the total poleward heat transport in the northern hemisphere and account for as much as 28 percent as far north as 50°N.

A second numerical experiment, complementary to that suggested above for the atmosphere, is one in which the polar sea ice is completely removed. The simulated surface heat flux and poleward oceanic heat transport could then be re-examined. Interesting variations on such an experiment would be one in which the pack ice was retained but the presence of leads considered and one in which the salinity's role in the determination of the density gradients was isolated.

D.4.3 Statistical/Dynamical Models

Experiments with atmospheric and/or oceanic models in which the large-scale transient eddy fluxes of heat and momentum are statistically parameterized

D.6 SUMMARY AND RECOMMENDATIONS

D.6.1 Summary

The general problem of global climate is being considered by the USC-GARP Panel on Climatic Variation (W. L. Gates and Y. Mintz, co-chairmen). While this panel has not given specific attention to numerical experiments in the polar regions, it has made a number of preliminary recommendations [USC-GARP draft report, Group I] relevant to the present report. These may be summarized as (1) investigation of the simulated mean and variability of monthly to decadal climatic states with global dynamical models, with emphasis on those factors that critically affect the atmosphere's thermal forcing (such as air–sea interaction processes, sea ice, and clouds); (2) increased efforts to achieve a realistic coupling of the atmosphere, ocean, and ice in a single dynamical model; and (3) investigation of the sensitivity and accuracy of statistical/dynamical (implicit) models as applied to the problems of climatic change.

D.6.2 Recommendations

In view of the present availability of suitable numerical models, and the modest cost of simulation experiments (as compared with field experiments), we *recommend* the following within the (pre-FGGE) time frame of POLEX:

D-1. *The Arctic performance of global atmospheric general circulation models should be systematically reviewed, with particular attention to the simulated components of the surface heat balance and the cloudiness.*

D-2. *The accuracy of atmospheric models' parameterizations of the sensible heat flux, evaporation, and stratiform cloudiness over both polar ice and ocean should be calibrated against comprehensive data sets specifically assembled for this purpose.*

D-3. *Increased efforts should be made to develop a realistic model of the growth and behavior of the pack ice.*

In support of these recommendations, we *urge* that numerical experiments be made with present global atmospheric models, and with both global and regional oceanic models, to study the climatic consequences of (a) the removal of the arctic ice pack; (b) the presence of leads in the ice pack; and (c) the effects of salinity, sea ice, and bottom topography on the circulation and heat transport within and into the Arctic Basin.

Subsequent to the FGGE, and as a POLEX-related contribution to an international climate research program, we *urge* the development of models of the coupled interactions of the atmosphere, ocean, and ice. Once such formulations are available, integrations over many years' length should be performed and the questions of the stability of the arctic ice pack and the dynamical relationships between arctic and worldwide climate re-examined.

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