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Maurice Ewing Volume 5

Climate Processes and Climate Sensitivity

Edited by
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Preface

The objective of this book is to contribute to the understanding of the sensitivity of the climate system by bringing together the work of modelers and others involved in the analysis of observational data. The approach considers climate variations and climate processes (focusing on climate feedback processes) on a broad range of time scales.

We have organized the book into conventional areas such as the atmosphere, ocean and cryosphere, but these are bound together by the feedback processes; thus the papers in different sections overlap extensively. If the book contributes a small amount toward a better understanding of the role which feedbacks play in coupling different parts of the climate system and in determining climate sensitivity, it will have served its purpose well.

We have included, following this preface, an introduction by E. E. David, Jr., President of the EXXON Research and Engineering Company. David speaks of another feedback process, the interactions between progressive understanding of the earth's climate and possible societal adaptation, particularly with regard to carbon dioxide climate effects. His thoughtful discourse should be of interest to those who study the climate system as well as to planners. There is a wide range of opinion as to when greenhouse climate effects will become important, but no doubt that eventually, as man-made climate effects become apparent, scientists will be pressed to provide the best possible data and understanding of the climate system.

This monograph discusses climate processes and climate sensitivity and is the result of a symposium held at the Lamont-Doherty Geophysical Observatory in Palisades, New York. The meeting was the fourth biennial Maurice Ewing symosium in honor of the founder and first director of the Observatory. The subject, differing from the topics in solid earth geophysics of the previous Ewing symposia, was chosen deliberately to emphasize the breadth of both Professor Ewing's research interests and the scientific contributions of the Observatory.

The symposium was made possible by a generous grant from the EXXON Research and Engineering Company, and was held October 25-27, 1982. Additional support was provided by the National Climate Program Office of the National Oceanographic and Atmospheric Administration, and by the Carbon Dioxide Research Division of the Department of Energy. We thank Wallace Broecker of L-DGO, David Rind and William Rossow of Goddard Institute of Space Studies, Hank C. Hayworth of EXXON for advice on the program, Margaret Swan for helping with the logistics and Andrea Calarco and Christy Bohol for handling and typing most of the manuscripts.

James Hansen
Taro Takahashi

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INVENTING THE FUTURE: ENERGY AND THE CO_2 "GREENHOUSE" EFFECT

E. E. David Jr.

President, Exxon Research and Engineering Company

Remarks at the Fourth Annual Ewing Symposium, Tenafly, NJ

Dennis Gabor, A winner of the Nobel Prize for Physics, once remarked that man cannot predict the future, but he can invent it. The point is that while we do not know with certainty how things will turn out, our own actions can play a powerful role in shaping the future. Naturally, Gabor had in mind the power of science and technology, and the model includes that of correction or feedback.

It is an important: Man does not have the gift of prophecy. Any manager or government planner would err seriously by masterminding a plan based unalterably on some vision of the future, without provision for mid-course correction. It is also a comforting thought. With man's notorious inability to create reliable predictions about such matters as elections, stock markets, energy supply and demand, and, of course, the weather, it is a great consolation to feel that we can still retain some control of the future.

As you may know, Exxon is a hundred years old this year; we have a long corporate memory of the very profound social and economic transformations that our business activities have helped bring about, and of how we and society have had to adapt further in response. That includes the at least temporary respite given to the whales through substituting kerosene lighting fuel for their rendered blubber; as well as the revolutionary changes wrought by the automobile and other machinery powered by liquid hydrocarbon fuels. The primary factors guiding such developments were technology and economic markets, though political systems also played their role.

But faith in technologies, markets, and correcting feedback mechanisms is less than satisfying for a situation such as the one you are studying at this year's Ewing Symposium. The critical problem is that the environmental impacts of the CO_2 buildup may be so long delayed. A look at the theory of feedback systems shows that where there is such a long delay the system breaks down unless there is anticipation built into the loop. The question then becomes how to anticipate the future sufficiently far in advance to prepare for it.

One answer is to invent the future in another way--through a system of contingency planning based on an assessment of a number of futures. As Harvey Brooks has noted, scenarios have limited use if they are merely surprise free projections of current trends; instead, they must somehow take into account those clouds on the horizon no bigger than a man's hand that can turn out to be dominant influences in twenty years. Inadequate scenario-making explains the poor performance of most social research to date--which so often gives the sense of too little too late, whether the topic is toxic waste, frost belt and sun belt, or the shift from manufacturing to information society. The key is to undertake research that will tend to be independent of future events, or, rather, relevant across a broad spectrum of scenarios.

This is not easy to do, but some of Exxon's own research and development strategy is aimed in that direction. And Exxon is not the only company with this attitude. That is why we and others in the petroleum industry have taken a strong interest in the issue of the greenhouse effect and your work. It is why we have participated in several initiatives to promote your research; it is why we are pleased to contribute to the holding of this symposium and to participate in it. And it is why we have begun our own modest research effort in the field, motivated also by the belief that perhaps the only way to understand a field is to do research in it. You have seen some of the results in a paper delivered yesterday afternoon. We are also in the process of evaluating the data on CO_2 concentrations collected over two years by an Exxon tanker plying between the Gulf of Mexico and the Gulf of Arabia.

Organization

Few people doubt that the world has entered an energy transition away from dependence upon fossil fuels and toward some mix of renewable resources that will not pose problems of CO_2 accumulation. The question is how do we get from here to there while preserving the health of our political, economic and environmental support systems. What I will do in the remainder of this talk is indicate how the world may invent a successful energy future, using the sort of corrective feedback system I have described. My perspective is of course an Exxon perspective, reflecting our own assumptions about the economic and social paths societies will prefer. And since fossil fuels, and liquid chemical fuels, are really the heart of the energy and the CO_2 problem, I will focus on those.

My plan of attack is, first, to consider the implications of recent energy developments. Then I will describe some of the key assumptions that are guiding Exxon's own R&D planning and which, I think, we have in common with many other actors in the scene. Finally, I will go on to mention some of the technical possibilities that may present themselves well beyond our usual twenty-year outlook period, that is, fifty years or more into the future.

While I am far from certain about the details, I think you'll find that I'm generally upbeat about the chances of coming through this most adventurous of all human experiments with the ecosystem.

Recent Energy History

It is ironic that the biggest uncertainties about the CO_2 buildup are not in predicting what the climate will do, but in predicting what people will do. The scientific community is apparently reaching some consensus about the general mechanisms of the greenhouse effect. It is considerably less agreed on how much fossil fuels mankind will burn; how fast economies will grow; what energy technologies societies will foster and when; and so how fast the buildup will occur.

But we do know about the recent past and the present. In the aftermath of the energy price increase of the past decade, consumers have reacted to the price feedback mechanism very much as classic economic theory would predict. They have sharply reduced their energy consumption and, in particular, their consumption of oil. They have substituted other fuels like coal and nuclear for petroleum, although more coal use does increase CO_2 emissions. Consumers have also conserved by turning to more energy efficient technologies, including smaller cars in the U.S. And they have done without.

It is difficult to disentangle the effects of conservation from the effects of recession. According to a recent report from the International Energy Agency, they are about equal. We think conservation effects are larger, but regardless, energy consumers have certainly broken the lockstep relationship between economic activity and energy consumption that seemed to prevail for a quarter century following World War II. For example, according to the International Energy Agency, it now takes 16 percent less energy and 26 percent less oil to produce 1 percent more of output in the non-communist industrialized countries than in 1973.

This development carries great significance for the CO_2 buildup. Consumers and technologists have been inventing and applying a wealth of methods to extract more work from less energy. For example, as one of our own biggest energy customers, we at Exxon have stepped up the efficiency of our refineries by twenty percent since 1973. Because refining is so energy-intensive, the energy savings, and the corresponding reductions of CO_2 emissions, have been very large indeed. Last year the savings amounted to the equivalent of some 28 million barrels of oil--equal to the production from a world-scale, 50,000-barrel-per-day synthetic fuels plant. On top of that, we have set the goal of doubling our refining efficiency by the year 2000, and we think the goal is realistic.

How far will the conservation trend go? It is too early to say for sure, but we think the implications apply very far into the future. And how far will the energy mix tend to favor fuels, such as coal, that produce large amounts of CO_2, rather than fuels with high ratios of hydrogen to carbon, such as gasoline and methane? To some extent the answer to that question depends upon our ability to come up with a source of low cost hydrogen based on non-fossil energy--a point I'll return to later.

Fossil Fuel Outlook: Key Assumptions

In assessing alternative futures, I would offer three assumptions in the form of predictions about the use of energy and fossil fuels.

First, nearly all societies will continue to give primacy to economic growth. The human desire to improve material conditions burns as bright as ever, if not brighter. As we have seen most recently in Poland, governments that fail to deliver at least a convincing promise of growth suffer dire consequences as a rule. With the overall world population expected to double over the next 50 years, economies and energy use will have to grow at a good clip just to hold per capita incomes even. Naturally, the pressures for growth will be greatest in the developing world, where populations are growing fastest.

A second assumption, one that follows from the first, is that in pursuit of growth most societies will prefer least-cost energy alternatives. I say this with the recognition that at least a few developing countries will prefer options that utilize local resources in order to conserve foreign exchange or use local labor, no matter what the cost. An example is Brazil's resort to alcohol fuels extracted from its sugar cane. However, such exceptions will not materially alter the world future.

The third assumption is that societies will continue to prefer the efficiencies of fossil-based liquid fuels in transportation uses. Because conventional petroleum resources will not suffice to meet the demand, a major industry will begin to grow around the turn of the century to produce synthetic fuels from oil sands, oil shale, and coal.

Despite the trend toward electricity, the electric vehicle will have trouble making significant inroads in transportation markets over the next twenty years. One problem is storage, which is partly a problem of energy density. Today's lead-acid batteries store about 1/300th the energy of a like weight of gasoline. We can improve on that; in fact, Exxon is in the middle of developing a zinc-bromine battery with two to three times the capacity of conventional lead-acid batteries. Another problem is the cost of batteries. They are expensive, mainly because of the cost of raw materials and typically short life cycles. Incidentally, we expect that load leveling, rather than the electric car, will be one of the earliest applications of our new battery. However, we would certainly not rule out the electric car one day--perhaps initially in the form of hybrid vehicles powered by batteries in tandem with small gasoline or diesel engines.

Another alternative features electric guideway systems in which vehicles use batteries on the feeder roads and electrically induced power along the main arteries. But the capital costs of such a system would be immense--making it a viable option only for much richer societies than we can foresee.

Granted, liquid fuels-like all chemical fuels-have their share of problems. In burning they may synthesize some unfriendly substances--such as PNA's, NO_x, SO_x and CO_2. Still, there are also well-known problems with producing electricity through non-chemical means, such as nuclear power. Solar voltaics overcome many of these drawbacks, but the inherent problems of the duty cycle and storage make me skeptical that solar voltaics will penetrate a large fraction of the electricity market in the near future, except in remote applications.

But to reiterate my main theme, such assumptions only act as a guide in determining where R&D managers can most usefully concentrate resources for inventing the future, subject to correction and further feedback. In any case we are not up against fatal, malthusian limits to growth. On the distant horizon, we may discern a peaking of petroleum production; because for more than a decade the world has been consuming pertroleum faster than the industry has been replacing it. But remaining non-petroleum fossil fuel resources are immense. As an example, in 1980 oil and gas production accounted for nearly 70 percent of the world's production of fossil energy. But oil and gas reserves account for only a little over 11 percent of the world's estimated total recoverable fossil energy resources.

As a practical matter, you would surely agree that the world economy is committed to using fossil resources for some time to come. The massiveness of the energy system in place simply forbids immediate displacement of one fuel or energy source by another. Historical market studies going back to wood and coal confirm this idea, suggesting that a new energy source requires about 50 years to achieve just half the total energy market.

What are Exxon's projections for fossil fuel use? Over the twenty years encompassed by our normal outlook we estimate the fossil fuel use will grow at the equivalent of about two percent per year. Much of this growth will occur in the developing countries, as they modernize their economies.

Beyond our normal twenty-year outlook period, we recently attempted a forecast of the CO_2 build-up. We assumed different growth rates at different times, but with an average growth rate in fossil fuel use of about one percent a year starting today, our estimate is that the doubling of atmospheric CO_2 levels might occur sometime late in the 21th century. That includes the impacts of synfuels industry. Assuming the greenhouse effect occurs, rising CO_2 concentrations might begin to induce climatic changes around the middle of the 21th century.

Manufacturing synthetic fuels will produce more CO_2 than conventional petroleum fuels, but the impact of substituting synthetics for depleting petroleum supplies will be relatively small. If, in our estimate, we back out synfuels and replace them with conventional petroleum fuels, the difference in CO_2 emissions would only add about five years to the doubling time. This is a highly conservative estimate, because it assumes that industry in the 21st century will continue using today's "Dinosaur" technologies for manufacturing synfuels, with no increase in the efficiency of these highly energy-intensive processes. And it takes no notice of the trends we are already seeing today in this budding information age. As John Pierce, the inventor of satellite communcations, likes to say, soon we may be traveling for pleasure but communicating to work. Such developments could eventually go very far in reducing the energy intensity and CO_2 emissions of advanced economies.

Exxon's Response in Science and Technology

The real point of these extrapolations is to get an understanding of how soon the problem may become serious enough to require action. And the lesson is that, while the issue is clearly important, we can still afford further research on the problem. And the world will have time to accumulate the material and scientific resources required to contend with the problem.

The same point is emphasized in the energy study published last year by the International Institute for Applied System Analysis, or IIASA. The study involved some 150 top scientists at one time or another and represents one of the most comprehensive assessments of the outlook for the next 50 critical years of what may well be in absolute terms the world's period of greatest population growth.

The IIASA study concludes that to make a successful transition from fossil fuels to an energy system based on renewable resources, the world economy must expand its productive powers. It must expand in all dimensions, but, most importantly, in the new knowledge and human skill that enlarge the technological base. For such knowledge and skill more than brute capital, is what enables societies in this age to use the same or even fewer resources to produce more.

The IIASA strategy for inventing that future resembles the one I have suggested: a strategy first, of gradual transition from clean, high quality resources--natural gas and oil--to dirtier unconventional fossil resources. The study also takes note of the CO_2 issue, recommending that society incorporate sufficient non-fossil options in the energy supply system so as to allow expansion of that base, if necessary, as the effects of carbon dioxide become better quantifiable through further research.

That means pursuing research leads in technologies that may not seem attractive by the fashionable standards of financial analysis. In a recent landmark article, Professors Hayes and Abernathy of the Harvard Business School warn strongly against such financially biased practices in American Industry; trying to outguess the economics of untried and untested technological approaches can be the death of an industry, and I might add, of a society, too. Some of the tools of this trade--for example, discounted cash flow analysis--are completely unrealistic. Sometimes they are called the Astrophysics of a non-existent universe.

As I have already suggested, Exxon's own R&D philosophy dictates searching for a diversified mix of short- and long-range technological options. I have already alluded to our efforts to boost the energy efficiency of our refineries--a highly immediate and apparent need to management. This need is apparent even though our R&D in some areas may not pay out for years--for example, in advanced separation systems that do not employ normal heat distillation techniques. Another of our major thrusts is in developing more versatile technologies for converting crude residuums to light transportation fuels. The need stems from an evident shift of demand in that direction and from the reduced quality of the average crude oil today. Exxon has begun deployment of an innovation in this area called FLEXICOKING, a processing "garbage can" that can convert virtually any heavy crude or residuum into transportation fuels and fuel gas.

As industry moves down to lower quality resources, there is synergism between such "resid" conversion technologies and our efforts to develop improved synthetics technologies. With the exception of established synthetics operations in South Africa and Canada, falling crude prices and escalating project costs have nipped the synthetic fuels industry in the bud. Many synthetics technologies have turned out to be far more expensive than anyone thought. So price feedback has told us that we must use R&D to bring capital and operating costs down through developing synthetics technologies adaptable to local conditions, resources, and markets. In the process, as I suggested earlier, we will certainly succeed in increasing their efficiency and so reducing CO_2 emissions. In the crucial conversion step, many of today's synthetics technologies operate at efficiences in the range of 60 percent. By the year 2000 we see possibilities for stepping up those efficiencies to nearly 80 percent. And this is not a fundamental limit.

Exxon is working on a very wide variety of synthetics options, including advanced shale retorting and direct coal liquefaction; a catalytic process for producing methane directly from coal; the generation of CO and Hydrogen, or synthesis gas, from coal, lignite, or remotely located natural gas; and the conversion of synthesis gas to fuels and chemicals. On the non-fossil fuel side, Exxon has for many years been doing R&D aimed at improving the fabrication of nuclear fuel elements; and we have been one of several companies in the race to produce cheaper solar voltaic cells made from amorphous silicon.

These efforts suggest primarily the early stages of the transition. For the later stages, some interesting options are beginning to present themselves. A prime difficulty with synthetics resources is their high carbon content. Chemically, that means low ratio of hydrogen to carbon. While the ratio is about four to one in natural gas and 1.8 in crude oil, it is only about 1.5 in oil sands bitumen or raw shale oil, and less than one in coal. In simple terms, a result is that producing these fuels means generating larger amounts of CO_2 than to produce comparable fuels from petroleum. Synfuels require more processing to manufacture and hence more processing heat generated by burning part of the resource.

Prompted by concerns about CO_2 emissions, among other things, some people have suggested a hydrogen economy, a fuel cycle based on hydrogen generated from water not using heat generated by fossil fuels. Perhaps there are ways to generate cheap hydrogen which could then feed directly into a synthetics process. One possible method would be to use thermochemical processes to split water, with advanced solar collectors or nuclear reactors supplying the process heat. The IIASA study notes that in manufacturing coal synthetics such a scheme would cut CO_2 emissions by one-fourth to one-third, compared to the usual coal conversion technologies envisioned. If they could generate hydrogen cheaply, such technologies would also cut overall costs sharply. For example, in the Exxon donor solvent coal liquefaction process, hydrogen accounts for well over a third of the total cost of producing coal liquids.

Summary and Conclusion

To sum up, the world's best hope for inventing an acceptable energy transition is one that favors multiple technical approaches subject to correction--feedback from markets, societies, and politics, and scientific feedback about external costs to health and the environment. This approach is not easy, or comforting to the uninitiated, because there is no overall neat and understandable plan. But prophecies leading to masterminded solutions that commit a society unalterably to a single course are likely to be dangerous and futile. A good sign is that, without any central plan, the world economy has already adopted conservation technologies that are reducing the rate of CO_2 buildup.

In shaping strategies for energy research and development, we must recognize that, generally, societies will give primacy to economic growth, to least-cost energy alternatives, and, in most transportation uses, to liquid fuels. Fortunately, these conditions give science and engineering a lot of room to maneuver. It appears we still have time to generate the wealth and knowledge we will need to invent the transition to a stable energy system.

I hope I do not appear too sanguine about the collective wisdom of our species. History bears ample testimony to the human capacity for grievous folly, as well as achievement and excellence. Clearly, there is vast opportunity for conflict. For example, it is more than a little disconcerting the the few maps showing the likely effects of global warming seem to reveal the two superpowers losing much of the rainfall, with the rest of the world seemingly benefitting. An acceptable future may require a degree of international cooperation that has eluded our grasp to date. An exception is of course science itself and in particular climatology, which even by the standards of science has been distinguished by a remarkable degree of interdisciplinary and international cooperation. As the world continues to grapple with the profound issues posed by the CO_2 buildup, it could seek few better models of international cooperation than what have already achieved.

FEEDBACKS BETWEEN DYNAMICAL HEAT FLUXES AND TEMPERATURE STRUCTURE IN THE ATMOSPHERE

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Abstract. Observational studies of meridional and vertical dynamical fluxes of heat and temperature structure in the atmosphere indicate that the primary dynamical modes affecting the temperature structure are large-scale eddies (mainly transient eddies) and moist convection. Theoretical parameterizations of these processes suitable for heat balance models are reviewed and the observational evidence supporting them is summarized. Some of the implied feedback mechanisms have been investigated with simple climate models and can have a sizeable impact on model sensitivity. Other dynamical feedbacks are omitted from current one-dimensional and two-dimensional models and have not yet been assessed. In particular, the impact on climate sensitivity of feedbacks associated with large-scale vertical eddy heat fluxes and β-effects need to be determined. It is advocated that simulations of seasonal changes in vertical and meridional dynamical fluxes and temperature structure be documented more thoroughly for general circulation models, as an aid in validating their simulations of dynamical feedbacks. The simulations of these feedbacks can be seriously compromised in experiments which use annual mean insolation or omit ocean transports.

Introduction

The fundamental drive for atmospheric motions is differential solar heating and the resulting gradients of entropy and temperature. The motions themselves transport heat and modify these gradients and consequently play a fundamental role in determining the climate of the atmosphere-earth-ocean system. Similarly, the feedbacks between the dynamical heat transports and temperature structure play a crucial role in determining how sensitive the climate system is to external change.

Much of what is known about the interactions between atmospheric motions and temperature structure is implicit in the modern theory of the general circulation of the atmosphere (see Lorenz, 1967, for a good summary of the modern theory and its development). However, the immediate stimulus for the development of this theory came from attempts to understand the momentum balance of the atmosphere, rather than its heat balance, and consequently atmospheric dynamicists did not turn their attention to the development of analytic theories of how atmospheric motions and temperature structure interact until the last dozen years or so. The stimulus for these more recent studies has come not only from an increased interest in climate problems, but also from an increased interest in other planetary atmospheres (e.g., see Stone, 1972, and Leovy, 1973). The problem of how atmospheric motions and temperature structure interact is fundamental to understanding not only climate sensitivity, but also the differences between planetary atmospheres.

There is still much that is not known about these interactions. In this paper we will focus on those areas where progress has been made -- in particular, we will focus on the interactions of meridional and vertical dynamical heat fluxes with meridional and vertical temperature structure on the planetary scale. We will not discuss zonal fluxes or interactions between dynamical fluxes and zonal structure -- these are potentially quite important, but they are not yet well understood. We will summarize and discuss both observational and theoretical studies of the interactions between the dynamics and the temperature structure; and also applications of climate models which tell us something about how these interactions affect climate sensitivity.

Symbols

a	radius of the earth
f	coriolis parameter, $2\,\Omega \sin\phi$
g	acceleration of gravity
H	density scale height, RT/g
N	Brunt-Vaisala frequency, $(\alpha g \frac{\partial\overline{\theta}}{\partial z})^{1/2}$

Table 1. Components of the Annual Mean Meridional Flux in the Northern Hemisphere

Component	Latitude where component is a maximum	Maximum flux	Flux at 35°
Ocean	20°	34 ± 11	23 ± 8
Atmosphere	45°	32 ± 2	25 ± 2
Atmospheric zonal mean motions	10°	9	-5
Atmospheric eddies	50°	37	30
Atmospheric eddy sensible heat flux	50°	28	17
Atmospheric eddy latent heat flux	30°	15	13
Total Atmosphere-ocean flux	35°	48	48

Units: 10^{14} Watts

Souces: Oort (1971), Vonder Haar and Oort (1973).

q_s	saturated specific humidity
R	perfect gas constant
T	temperature
u	zonal wind
z	height above the surface
C_p	specific heat at constant pressure
L_v	latent heat of vaporization of water
α	thermal expansion coefficient
β	$\frac{1}{a}\frac{df}{d\phi} = \frac{2\Omega}{a}\cos\phi$
ϕ	latitude
ρ	density
θ	potential temperature
Ω	angular rotation rate of the earth
K	eddy mixing coefficient
$\overline{(\ )}$	mean value of ( )

Meridional Fluxes and Meridional Temperature Structure

Components of the Meridional Flux

Table 1 summarizes observational results from Oort (1971) and Vonder Haar and Oort (1973) showing the contributions of various components of the dynamical flux to the annual mean meridional flux in the Northern Hemisphere. Both the maximum values and the values at 35°N, where the total flux is a maximum, are shown. Vonder Haar and Oort's estimates of the probable errors in their estimates of the ocean and atmosphere fluxes are also included. The ocean and atmosphere are equally important contributors, with the ocean carrying most of the flux in low latitudes and the atmosphere carrying most of it in middle and high latitudes.

In this paper we are only concerned with the flux carried by the atmosphere. However, it is clear that some understanding of the interaction between the ocean flux and temperature structure will also be necessary in order to understand climate and climate sensitivity. We do note that there is evidence that this interaction is very indirect -- the seasonal changes in the ocean flux do not correlate with the seasonal changes in the meridional temperature gradient (Stone and Miller, 1980). This is perhaps not surprising since surface wind stresses play a major role in driving ocean currents (Rooth, 1983). Thus changes in the ocean fluxes may involve changes in the momentum balance of the atmosphere as well as changes in the heat balance of the climate system.

The atmospheric flux may be divided into a component due to the zonal mean motion and a component due to eddies. Table 1 shows that the eddies are the dominant mechanism for transporting heat in the atmosphere. The eddies are primarily a middle and high latitude phenomenon, and in those latitudes their transports greatly exceed the transports by the zonal mean motions. Thus the non-interaction theorem for low dissipation systems, in which these two components sum to zero, does not apply to the atmosphere.

In low latitudes most of the atmospheric transport is accomplished by the zonal mean motions. However, the atmospheric transport in low latitudes is much less than the ocean transport. Thus an understanding of the former, without an understanding of the latter, is not very useful for furthering our understanding of climate. Consequently, we will not discuss the low-latitude transports by the zonal mean motions in the atmosphere. We note however that a good foundation for understanding this transport has been established by Schneider (1977) and Held and Hou (1980).

Atmospheric eddies carry heat in two primary forms, sensible heat and latent heat (the transports of potential energy and kinetic energy are negligible -- Oort, 1971). As shown in Table 1 both forms are important. Since the total atmospheric flux can be approximated by the sum of the eddy sensible and latent heat fluxes, we will concentrate our discussion of the meridional fluxes in the atmosphere on these two components.

Stationary Eddies vs. Transient Eddies

It is conventional to divide atmospheric eddies into transient and stationary components. About three quarters of the meridional eddy heat transport is associated with the transient eddies and one quarter with the stationary eddies (Oort, 1971). The stationary eddies arise from the stationary components of the eddy forcing, i.e., from topography, land-ocean contrasts in surface heating, etc. Transient eddies would exist even in the absence of such stationary forcing because of the baroclinic instability of the atmosphere (e.g., see Lorenz, 1967).

However, the distinction between transient and stationary eddies may be artificial as far as the meridional heat transport is concerned. There is considerable evidence that there is a very strong negative feedback between the stationary and transient components of the eddy heat fluxes and that the two components should be considered to be a joint response to differential heating. The evidence is a follows:

Experiments with General Circulation Models (GCM's). Manabe and Terpstra (1974) performed an experiment with the Geophysical Fluid Dynamics Laboratory (GFDL) GCM, in which all mountains were removed from the model. Thus in the experiment the forcing for stationary eddies in the northern hemisphere was greatly reduced, and the stationary eddy meridional heat transport was reduced by 75%. However, at the same time the transient eddy meridional heat transport increased by 70%, so that the total eddy transport was only decreased by 25%.

Correlations with changes in the temperature gradients. Stone and Miller (1980) correlated seasonal changes in the meridional eddy heat transports and the surface meridional temperature gradient. The results are shown in Fig. 1. The correlation for the total eddy flux is much larger than for the two individual components, and the correlations of the two components vary in a complementary way. This indicates that it is the total eddy flux rather than the individual components which is responding to changes in the temperature gradient.

Eddy energy cycles. The Lorenz energy cycles associated with the transient eddies and the stationary eddies are qualitatively similar. In particular the stationary eddies only transport a significant amount of heat in winter (Oort, 1971) and Holopainen (1970) has shown that the energy cycle associated with the stationary eddies in winter includes the following features:

i) zonal mean available potential energy is the main source of eddy available potential energy;

ii) eddy available potential energy is the main source of eddy kinetic energy;

iii) dissipation is the main sink of eddy kinetic energy, i.e., the non-interaction theorem does not apply.

The same features are characteristic of the transient eddy energy cycle (Oort and Peixoto, 1974) and they suggest that baroclinic instability is at work in both kinds of eddies. Yao (1980), using a greatly simplified process model has

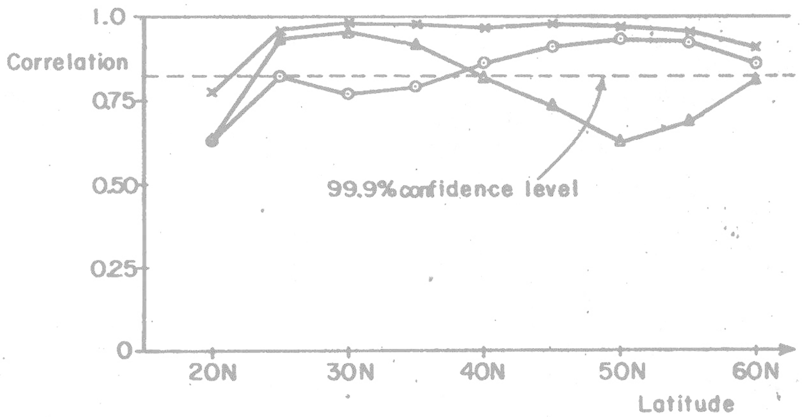

Fig. 1. Correlations between surface meridional temperature gradient and the meridional flux of sensible heat by all eddies (x), by transient eddies alone (Δ), and by stationary eddies alone (0) as a function of latitude. From Stone and Miller (1980).

demonstrated that, in a system which is sufficiently strongly unstable, baroclinically, the two types of eddies can in fact behave in a similar fashion.

All the theories that have been developed for how eddy fluxes interact with the temperature structure are in fact based on the hypothesis that heat-transporting eddies are generated by baroclinic instability. In light of the above evidence it is plausible that such theories will work well even when stationary forcing is important. In any case the transient eddies are more readily identified with baroclinic instability and they are the main contributors to the total eddy meridional heat flux.

Eddy Sensible Heat Flux

The most sophisticated parameterization for the meridional eddy sensible heat flux developed to date, i.e., the only one that includes β-effects, is that of Branscome (1980, 1983). He used approximate analytic solutions of Green's (1960) model of baroclinic instability to derive a general expression for the characteristic vertical structure of the most unstable baroclinic wave. This general expression allowed him to combine the parameterizations of Stone (1972) and Held (1978) which are applicable to deep waves ($\beta \rightarrow 0$) and shallow waves ($\beta \rightarrow \infty$), respectively. All of these parameterizations are based on mixing length theory, with the meridional mixing length taken to be the radius of deformation, and the eddy velocity amplitude taken to be equal to that of the zonal mean flow. The former choice has been shown to be appropriate for baroclinic waves by Killworth's (1980) analysis of the baroclinic instability problem with the effects of meridional shear included. The latter choice can be derived by extrapolating the results of analyses of finite amplitude baroclinic instabilities (e.g., Pedlosky, 1970 and 1979) to conditions far from neutral stability.

Branscome's general result for the meridional eddy flux of sensible heat per unit area is

$$F_{MESH} = 0.6 \frac{\rho\, C_p\, N\, d^2}{\alpha\, g} \left(\frac{\partial \bar{u}}{\partial z}\right)^2 e^{-z/d} \qquad (1)$$

where

$$f \frac{\partial \bar{u}}{\partial z} = - \frac{\alpha\, g}{a} \frac{\partial \bar{T}}{\partial \phi} \qquad (2)$$

$$d \approx \frac{h\, H}{h + H} \qquad (3)$$

and

$$h = \frac{f^2 \frac{\partial \bar{u}}{\partial z}}{\beta\, N^2} \qquad (4)$$

The dependence of the flux on the temperature structure, i.e., on $\partial \bar{T}/\partial \phi$ and $\partial \bar{\theta}/\partial z$ (which enters through N), is rather complicated, but can be written simply in the two extreme cases studied by Stone and Held. In these cases we obtain for the vertical integral of the flux:

$\underline{\beta \rightarrow 0\ (d \rightarrow H)}$:

$$\int_0^\infty F_{MESH}\, dz \propto \left(\frac{\partial \bar{\theta}}{\partial z}\right)^{1/2} \left(\frac{\partial \bar{T}}{\partial \phi}\right)^2 \ , \qquad (5)$$

$\underline{\beta \rightarrow \infty\ (d \rightarrow h \rightarrow 0)}$:

$$\int_0^\infty F_{MESH}\, dz \propto \left(\frac{\partial \bar{\theta}}{\partial z}\right)^{-5/2} \left(\frac{\partial \bar{T}}{\partial \phi}\right)^5 \ . \qquad (6)$$

The flux increases monotonically as $\partial \bar{T}/\partial \phi$ increases, so there is a negative feedback be-

ux and the temperature gradient. As
stability increases, the flux increases
m value and then decreases.
me (1983) has shown that the above
ation gives realistic magnitudes for
ensible heat flux and has a qualitatively
height and latitude dependence. The best
how the flux depends on the temperature
re comes from observations of seasonal
. In seasonal changes there is very little
in the static stability in low and middle
es, so one can use the observed changes to
r the dependence of the flux on just the temperature gradient. Stone and Miller (1980)
umed a functional dependence of the form

$$\int_0^\infty F_{MESH}\, dz \;\alpha\; \left(\frac{\partial \overline{T}}{\partial \phi}\right)^n \qquad (7)$$

and derived values of n from the seasonal changes. In high latitudes β → 0, h → ∞, and d → H, so one would expect from the parameterization that Eq. (5) would apply. In low latitudes f → 0, h → 0, and d → h, so one would expect that Eq. (6) would apply. Stone and Miller's results for the exponent, n, are shown in Fig. 2 and are in fact consistent with these expectations. A regime corresponding to deep waves appears to apply in mid-latitudes (Eq. 5), while a regime corresponding to eddies of intermediate height (with a sensitivity intermediate to Eqs. 5 and 6) appears to apply around 30°N.

Eddy Latent Heat Flux

A simple and effective way for calculating eddy latent heat fluxes has been suggested by Leovy (1973), based on the following approximations:

i) fluctuations in relative humidity are small compared to fluctuations in specific humidity

ii) fluctuations in temperature are small compared to mean temperatures

iii) the relative humidity is approximately 100%.

The first two approximations are quite good for typical baroclinic waves, and the last is reasonable for at least the lowest layers of the troposphere, where most of the latent heat fluxes are concentrated. The first and third approximations work because of the presence of the oceans over much of the earth's surface, so that, in effect, there is an infinite moisture source at the surface which keeps the atmosphere nearly saturated in its lowest layers.

With the above approximations the meridional eddy flux of latent heat per unit area can be related to the eddy flux of sensible heat per unit area as follows (Mullan, 1978):

$$F_{MELH} = \frac{L_v}{C_p} \frac{\partial q_s}{\partial T} F_{MESH} \qquad (8)$$

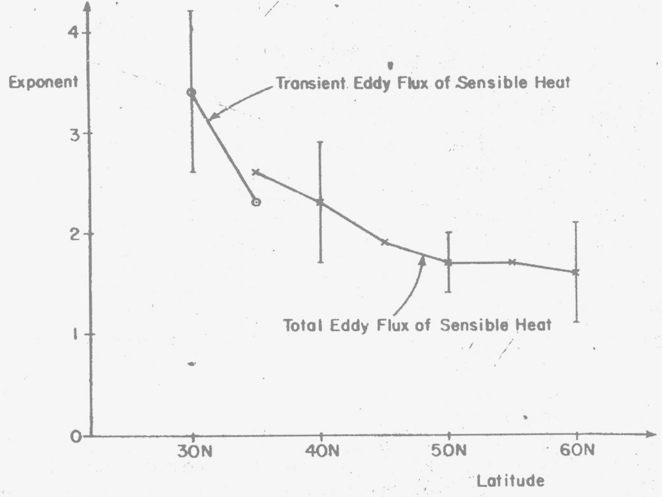

Fig. 2. Exponent in Eq. (7) which gives the best fit between the integrated eddy sensible heat flux and the surface meridional temperature gradient at various latitudes. The transient eddy flux closely approximates the total eddy flux at 30°N and 35°N. From Stone and Miller (1980).

This implies that the eddy latent heat flux reinforces the same feedbacks present in the eddy sensible heat flux. In addition, it interacts strongly with the temperature field because the saturated specific humidity, q_s, is very sensitive to temperature. According to the Clausius-Clapeyron equation, for typical temperatures,

$$q_s \;\alpha\; e^{-\frac{5400°K}{T}} \; . \qquad (9)$$

Therefore small increases in temperature lead to relatively large increases in the latent heat flux. This is turn increases the moisture convergence, precipitation, etc. Consequently, the heat flux and the hydrological cycle will be rather sensitive to the temperature of the system. This sensitivity has been demonstrated in experiments with the GFDL GCM (Manabe and Wetherald, 1980; Manabe and Stouffer, 1980). The former study also illustrated the feedback between eddy sensible heat flux and temperature gradient: an increase in CO_2 caused an increase in temperature and eddy latent heat flux, and this in turn caused a decrease in meridional temperature gradient and eddy sensible heat flux (see Eqs. 5 and 6).

Mullan (1978) used observations to test the validity of the above parameterization. A comparison of the observed and calculated moisture fluxes is shown in Figs. 3 and 4, for January and July, respectively. The main error in the parameterization occurs in lower latitudes, particularly in summer at 20°N to 35°N. The error is due to the parameterization's not being able to represent transports associated with monsoonal