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"Progress in Geophysical Fluid Dynamics"

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Progress in Geophysical Fluid Dynamics

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ABSTRACT

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Geophysical fluid dynamics deals with the motions and physics of the atmosphere, oceans and interior of the earth and other planets: the winds, the swirls, the currents that occur on myriads of scales from millimeter to climatological. Explanations of natural phenomena, basic processes and abstractions are sought. The rotation of the earth, the buoyancy of its fluids and the tendency towards large-scale turbulence characterize these flows. But geophysical fluid dynamics is importantly a part of modern fluid dynamics which is contributing to the development of nonlinear mechanics generally. Some general insights are emerging for nonlinear systems which must be regarded as partly deterministic and partly random or which are complex and aperiodic. Contributions from geophysical fluid dynamics come from its methodology, from the experience of examples, and from the perspective provided by its unique scale. Contributions have been made to turbulent, chaotic and coherently structured nonlinear process research.

Turbulent vortices larger than man himself naturally invite detailed investigation and deterministic physical studies. Examples are storms in the atmosphere and large ring vortices spun off by the Gulf Stream current in mid-ocean. The statistics of these events determine critical aspects of the general circulations. Fluid dynamicists generally now know that it is often relevant or necessary to study local dynamical processes of typical eddies even though only the average properties of the flow are of interest; progress in understanding the turbulent boundary layer in pipes involves the study of millimeter-scale vortices. Weather-related studies were seminal to the construction of the new scientific field of chaos. Coherent vortices abound of which the Great Red Spot of Jupiter is a spectacular example.

Geophysical fluid dynamicists have been among forefront researchers in exploiting the steadily increasing speed and capacity of modern computers. Supercomputers today are powerful enough to allow realistic simulations of turbulent and planetary flows. A school of scientists and philosophers regard such simulations of computational physics as representing the first major advance in scientific methodology in centuries: scientific enterprise is now tripartite, with simulation on a par with theory and experimentation. Data assimilation involves the continual blending of observational data with dynamical model output for the best overall representation of reality. The conceptual model of nature implied is novel.

The named discipline of geophysical fluid dynamics is barely three decades old. Scientifically it is an interesting time in the history of human development on earth as aspects of the dynamics of our atmosphere and oceans become solved problems. Geophysical fluid dynamicists are ready to deal with interactive and whole-earth problems, and to continue to expand the horizons of their science via the opportunities provided by space exploration. Progress is occurring in understanding climate and climate change processes which involve dynamical coupling of the oceans and the atmosphere and which cause profound biological and economic effects. Applied geophysical fluid dynamics is essential for the potential success of the International Geosphere-Biosphere Program which seeks to unite earth scientists in the next decade in the pursuit of global change research dedicated to a more habitable planet.

INTRODUCTION

This review is concerned with the science of geophysical fluid dynamics, its progress, status and directions, its place in science generally, and its impact on mankind's ability and potential to live successfully on our planet. Two scientific themes of general interest occur. The first is progress in the conceptual basis of nonlinear dynamics. The second is the emergence of computer simulations so powerful and realistic as to constitute a novel

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scientific methodology. Geophysical fluid dynamics deals with the motions and physics of the atmosphere, oceans and interior of the earth and other planets—the winds, the waves, the currents that occur on myriads of scales from millimeter to climatological. Explanations of natural phenomena and of basic processes, and abstractions, are sought. The rotation of the earth, the buoyancy of its fluids and the tendency towards large-scale turbulence characterize these flows.

PHENOMENOLOGY: SCALES AND BASIC PROCESSES

Fig. 1 shows the circulation and flow in the earth's atmosphere as revealed by patterns of clouds, as viewed from a space-satellite. The north polar ice cap is visible at the top. North America is at the upper right, and Australia at the lower left. The many scales and features of motion exhibit structured order but also disorder and turbulence. There is a gen-

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Fig. 1. Circulation and flow in the Earth's atmosphere as revealed by cloud patterns. After fig. 1 in EdSC (1977). See also Pedlosky (1979).

eral zonal banding of features (that is, an alignment parallel to the equator) most evident in the cloud band girdling the equator, but also evident in the mid-latitude Jet Stream associated with the cold front, waves and patterns of cyclones and anticyclones seen "snaking" across the upper half of the earth. The Jet Stream is planetary scale, the cyclones that ride on it are about 2000 km in extent, the elongated fronts only about 100 km across, and 20 km clumps of cumulus clouds form the organized large cumulus groups. Smaller-scale streamers and wisps are also evident. To appreciate further the multitude of scales and features we shall take two successive zooms in on smaller pieces of the atmosphere. Fig. 2 shows clearly the Gulf of California as a feature of the California–Mexico coastline with the North Pacific Ocean at the bottom. Over the continent in the right half of the figure is a frontal system and (top of the picture) a cyclone associated with the Jet Stream. Fig. 3 zooms to a section of a cold front covering a region only about 5000 km on a side. Again order and disorder are apparent. On this scale we can see (lower right) approximately 20 km wave bands streaming from the cumulus mass. (These are internal gravity waves as are the faint steaks across the image which are waves in high cirrus clouds as revealed by ice crystals.)

We turn now to the circulation and flow in the ocean. There is a conceptual similarity in the range of scales, variety of structures and appearance of order and disorder, and a dynamical analogy of sorts between features such as the oceanic Gulf Stream current and

Fig. 2. Frontal system and cyclone associated with the Jet Stream. After fig. 2 in EdSC (1977).

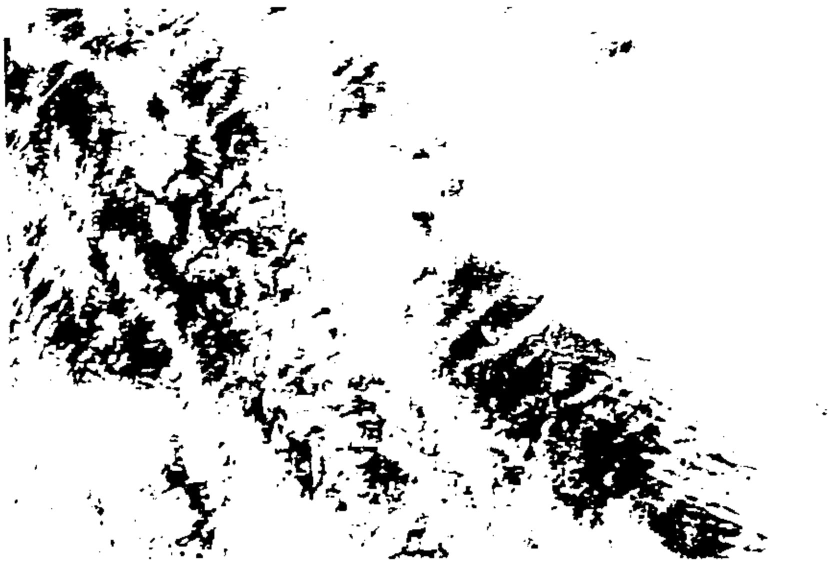


Fig. 3 Cold front, waves and turbulence. After fig. 4 in EdSC (1977)

the atmospheric Jet Stream. Oceanic features of 10 km or larger in horizontal extent tend to have a simple vertical structure from sea surface to bottom. Thus sea surface tracers, which can be viewed by satellite, are useful indicators for deep sea motions. Fig. 4 shows the same features in the western North Atlantic as revealed by two tracers, the color of the sea surface (on the top) and the temperature of the sea surface (on the bottom). To interpret these pictures we note firstly: that color is due primarily to the pigment concentration arising from phytoplankton which are very small plants (in the black-and-white version high concentration is dark and low is light); secondly, the temperature pattern is coded for pictorial representation (warm is light, cold is dark). The coast line is the northeastern United States and Canada; notice the clear shape of Massachusetts. Dominant features are the meandering Gulf Stream (indicated by numeral 3) separating cold water rich in pigment to the north from warm, infertile water to the south. The Stream, only 50 km wide, has 300-km waves and extends for thousands of kilometers downstream. There are wisps, streamers and eddies on many smaller scales. Noteworthy is the large circular ring-eddy (numeral 5) of warm infertile water but north of the Stream. We know that this feature, now a stable, coherent vortex, snapped off from an intense meander of the Gulf Stream in a violent turbulent event several months earlier. Finally we draw attention to the obvious correlation between the physical structures and the phytoplankton distribution. The phytoplankton distribution is representative of the overall biological productivity of the life-system on all scales (the ecosystem). We will return to this important relationship later.

To conclude the discussion of scales we examine the distribution of surface temperatures over the globe. Fig. 5 shows the averages for the months of January (a) and July, 1979 (b). Warmest is dark and coldest is light. The averages smear many of the features and eliminate the smaller scales of the instantaneous, turbulent "snapshots" we have seen previously. The Gulf Stream now appears simply as a warm plume spreading out into the North Atlantic. The seasonal cycle is periodic; it is an ordered, recurring scale of motion longer than the turbulent fluctuations which have been averaged out. The overall patterns are predominantly zonal, but substantial east-west oriented features appear.

due to ocean circulation and to air-sea-land interactions. The global surface temperature is an important climatic variable related to

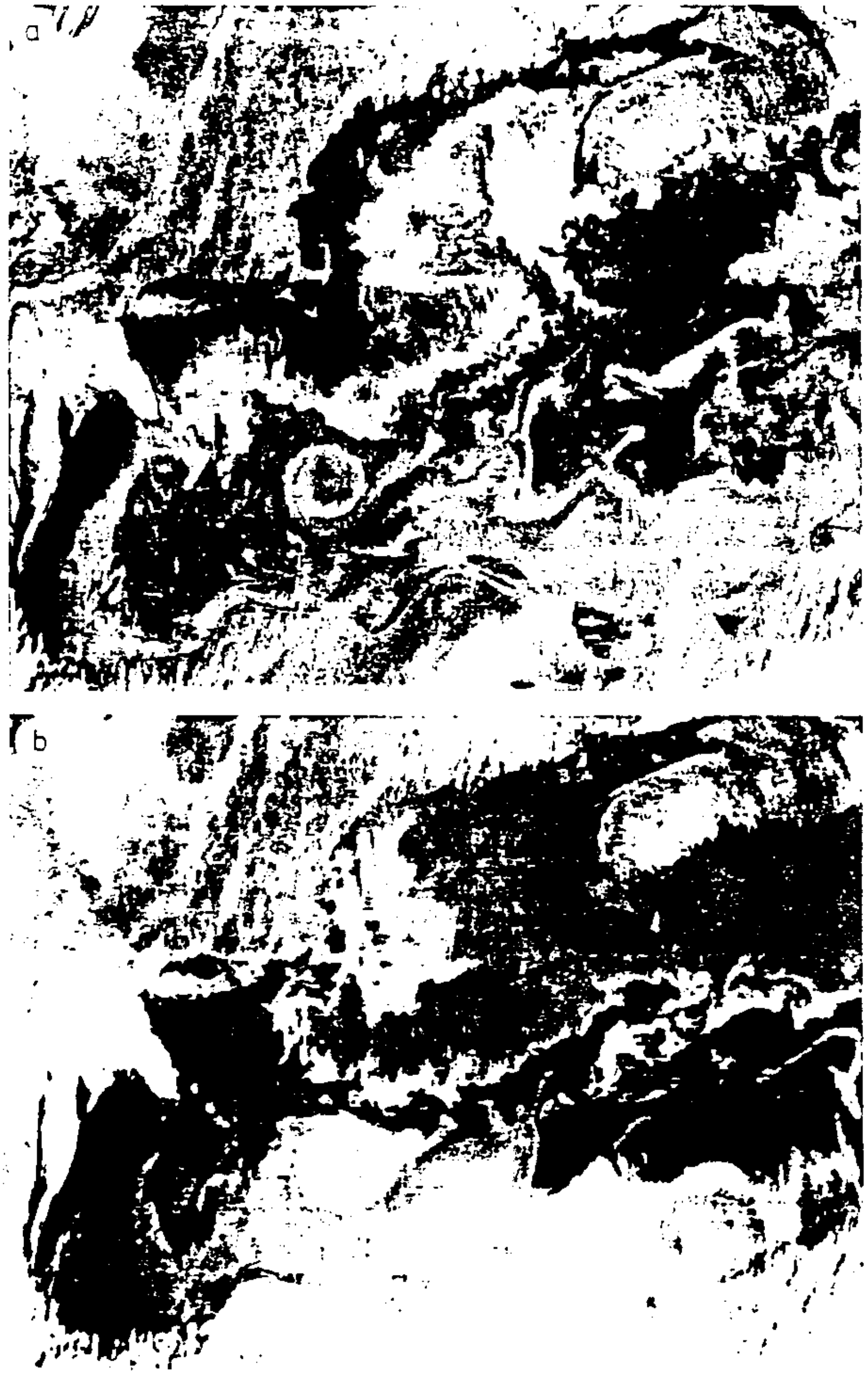


Fig. 4. Circulation and flow in the western North Atlantic Ocean as revealed by surface patterns of (a) color (phytoplankton) and (b) temperature patterns (NASA, 1984). Provided through the courtesy of the National Aeronautics and Space Administration, Washington, DC.

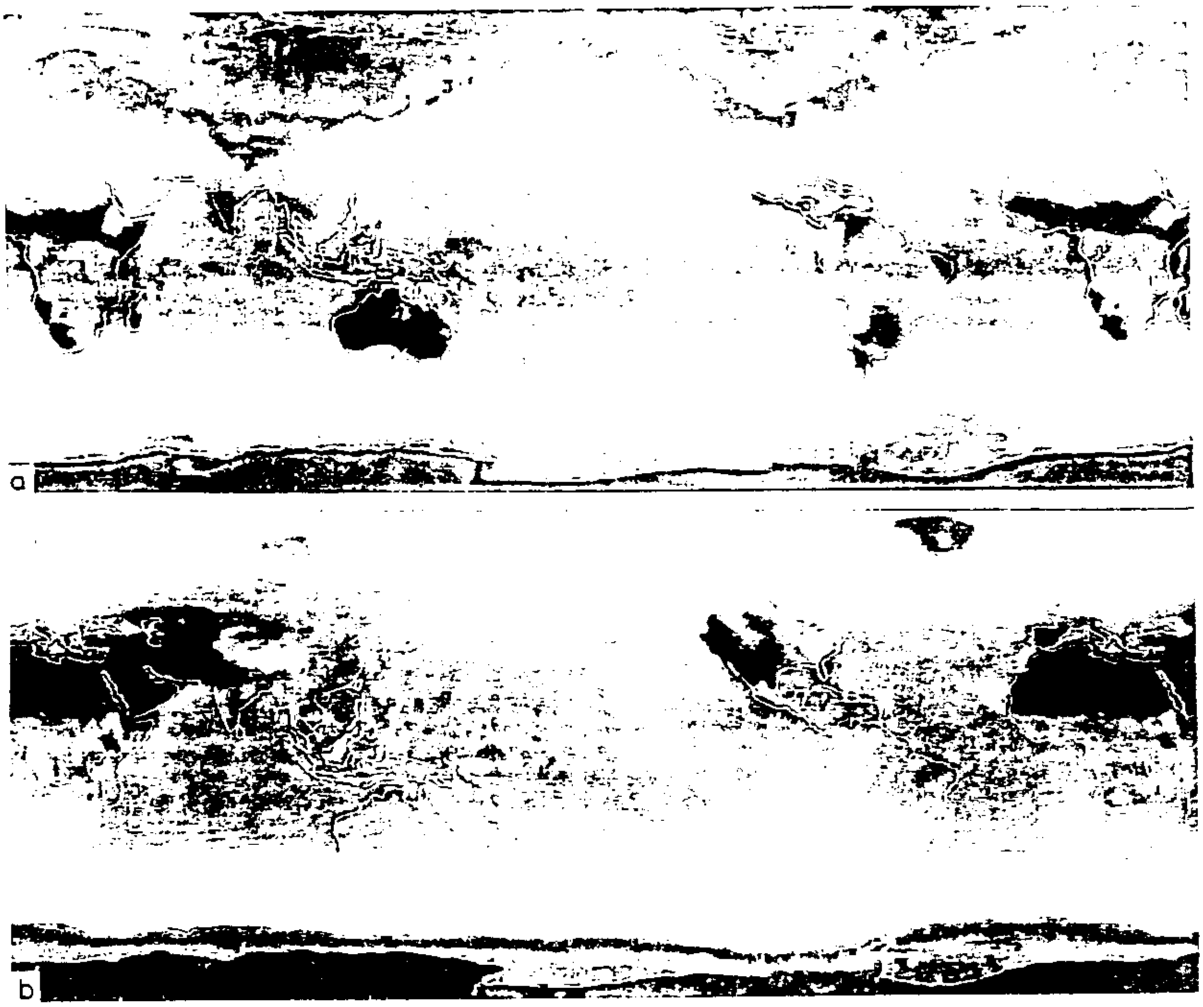


Fig. 5. Global surface temperature in (a) January and (b) July (NASA, 1984). Provided through the courtesy of the National Aeronautics and Space Administration, Washington, DC.

biology, agriculture and commerce controlled by interactions of the planetary fluids. We will return to this theme later also.

The rotation of the earth, the buoyancy of its fluids, and the tendency towards large-scale turbulence characterize the flows on our planet. It helps to understand these processes by comparisons with other planets and by laboratory scale-model experiments, as well as by direct examination of the phenomena themselves. We now know, from the fly-by of the Voyager-2 spacecraft in January 1986, that there are zonally oriented bands of clouds on the large planet Uranus which is nineteen times further from the sun than is Earth. The photographs of these bands are shown in Fig. 6: through a violet filter (upper left), an orange filter (upper right) and a methane orange filter (lower left). The composite, color-enhanced image is shown in the lower right-hand corner. The coordinate grid is centered on the rotational north pole, but the white dot is the point on the planet directly under the sun! This is remarkably different than Earth, and provides insight. Fig. 7 compares Earth, Jupiter, and Uranus. It shows the direction of each planets rotation (indicated by the circular arrow), the orientation of the rotational axis relative to the beam of incoming sunlight, and the direction of the general circulation or planetary winds, as revealed by the cloud band patterns. Earth's cloud pattern is a

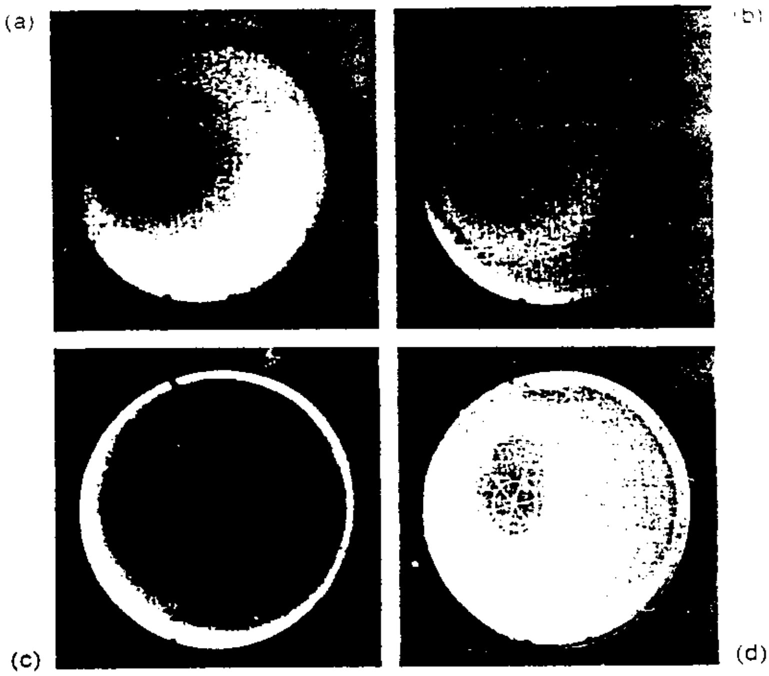


Fig. 6. Cloud bands on the planet Uranus as revealed with a (a) violet filter, (b) orange, (c) methane orange and (d) a composite picture. After Ingersoll (1987). Provided through the courtesy of the Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California.

schematic of our first figure which we know has predominant zonal features. The zonal banding relative to the rotational axis and equator of Jupiter and Uranus is very apparent. The sunlight provides the energy for the circulation but the striking fact is that the circulation is related first and foremost not to the pattern of energization but to the rotation. This indicates that the inertial force, the Coriolis force of planetary rotation is a dominant effect. Before leaving this figure, we note for later recall a large coherent vortex, the Great Red Spot of Jupiter.

The atmospheric general circulation "machine" is schematized in Fig. 8 with a comparison of Earth (lower) and Mars (upper). The atmospheres are transparent to sunlight which is absorbed near the surface, heating

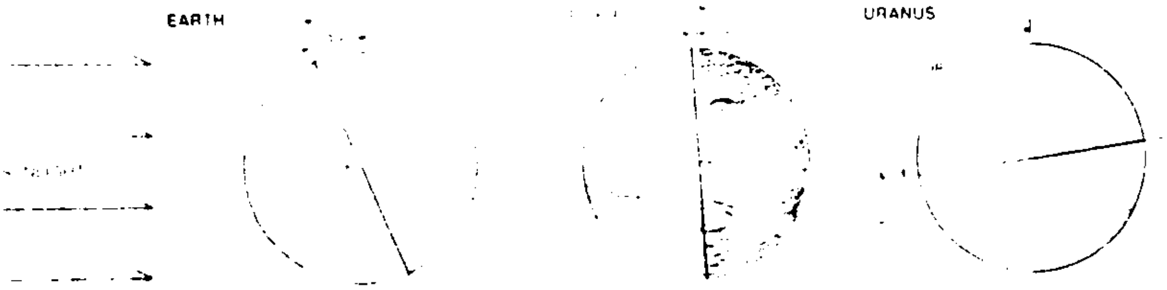


Fig. 7. The rotation of the planets and the sense of their general circulation. From Ingersoll (1987), copyright © January 1987 by Scientific American Inc. All rights reserved.

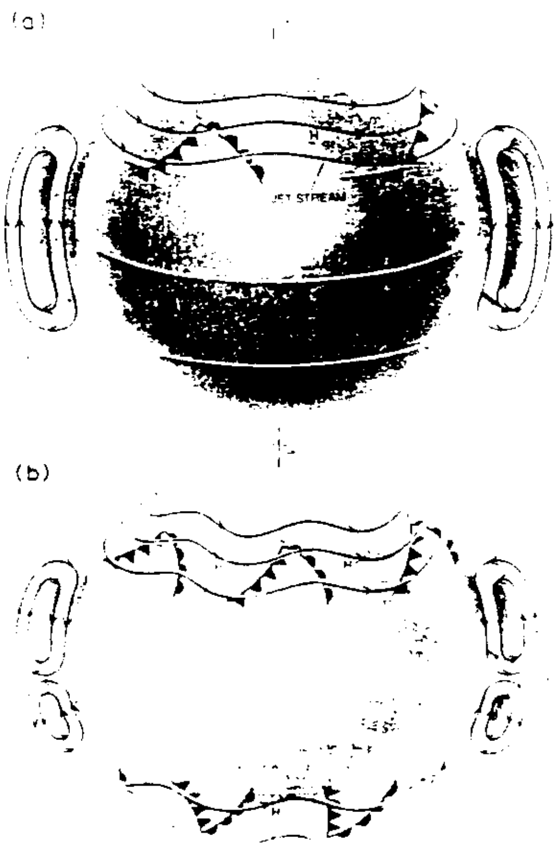


Fig. 8. General circulation schematics for (a) Mars and (b) Earth. After Haberle (1986), copyright © May 1986 by Scientific American, Inc. All rights reserved. See also Prinn and Fegley (1987).

the equatorial regions more than the polar. Warm air rises and cool air descends in convective cells (Hadley cells). The Coriolis force deflects the motion and causes zonal winds: here the strong mid-latitude upper tropospheric Jet Stream is sketched. Instabilities cause waves, cyclones and anticyclones on the Jet Stream. These are storms or weather systems. Here they are indicated by L and H for low and high pressure regions; earlier we saw real examples revealed in clouds. Dynamicists are interested in differences as well as similarities. Here it is northern hemispheric winter. The Earth remains reasonably symmetric about the equator but on Mars the southern hemispheric equator to poleward heat gradient is too small for the formation of jets and storms. Mid-latitude circulation and weather systems were first modeled in the laboratory in the 1950's. Fig. 9 illustrates a laboratory analogue of a mid-latitude weather map. Four cm of fluid are rotated at 30 rps about the vertical axis in a tank of 20 cm radius. The heating of the outer rim, which models an equatorial latitude, and the cooling of the center, which models a polar latitude, drives the circumferential (azimuthal) jet whose instabilities produce the waves and eddies of weather. We are a stationary observer in the rotating system, looking down on the top at the flow pattern revealed by aluminium particles in a streak photograph. Such experiments are important because they allow for controlled and quantitative study of rotational and buoyancy processes.

Certain basic fluid processes occur throughout geophysical fluid dynamics and manifest themselves in diverse situations and over a vast scale range. An elegant example is afforded by Rayleigh-Benard convection or convective overturning due to heating from below and cooling from above. Sometimes when the coffee cools in your cup, you can observe a convection pattern revealed by the cream on the surface. Fig. 10 shows an ordered pattern of convecting hexagons occurring over a uniformly heated copper plate in the laboratory. The view is from above and the pattern is revealed by aluminium powder. The upward moving regions appear clear and dark, as the powder collects in the convergence zones above the downward moving regions. The rising and sinking of similar convectively overturning cells is shown from a sideways view in the top panel of Fig. 11. Here the geometry of the laboratory container has favored convective rolls, with the rolling motion not changing with the coordinate direction into the paper. The intensity of heating has been increased in the middle panel, and the pattern distorted by rotating the experiment about a vertical axis in the lower panel. Convection occurs naturally throughout planetary and stellar atmospheres, and within planetary oceans and interiors. The patterns

Fig. 9. Laboratory model of experiment of mid-latitude atmospheric circulation. After fig. 136 in Van Dyke (1982) of an experiment by D. Fultz. See also Hide and Mason, 1970). By permission of the American Meteorological Society. (Fultz et al., 1959. Meteorological Monographs, 4 (21).)

of the stratocumulus cloud tops, shown in Fig. 12, are attributed by meteorologists to Benard convection. An extensive convective pattern is revealed by cumulus cloud puffs in Fig. 13. Here we are looking down the Florida Peninsula, which is several hundred kilometers across, from the north, with the North Atlantic Ocean on the left and the Gulf of Mexico on the right. It is late morning and as air moves off the cool water over the warm land and rises, water vapor reveals the rising motion of an almost regular convective pattern with about 20 km spacing.

Hot at the time of its formation, the planet earth has been cooling ever since and the interior core is still very hot. Thus the mantle, between the core and the crust which is cooling, is heated from below. The mantle convects. This is because it is a plastically deformable solid, that is, it acts like a solid for short-time scale processes. A schematic is shown in Fig. 14. We are looking sideways at a two-tiered model of mantle convection. The upper and lower mantle both have a cellular convection pattern (analogous to the sideways view of the convective rolls seen earlier in Fig. 11). The upper mantle convection drives plate tectonics, and plate tectonics is responsible for continental drift. Fig. 15 thus illustrates interior convection as revealed by the surface pattern of the continents shifting or drifting in time over the past 540 million

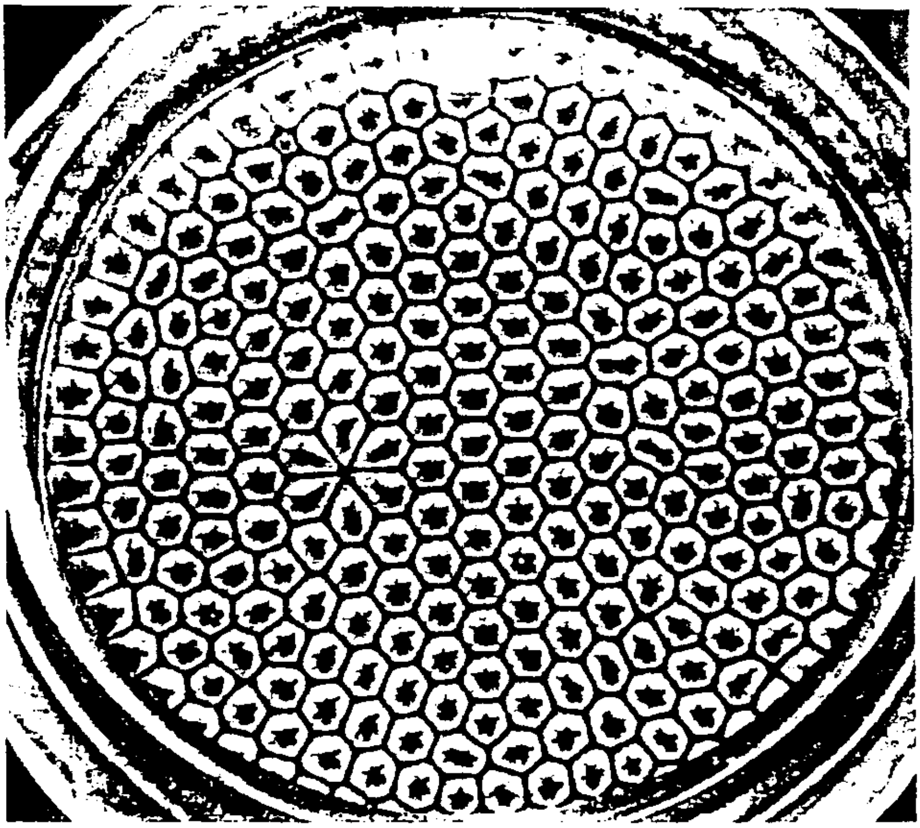


Fig. 10. Convection cells in the laboratory as viewed from above. After fig. 142 in Van Dyke (1982) of an experiment by Koschmieder. From Koschmieder (1974). See also Chandrasekhar (1961).

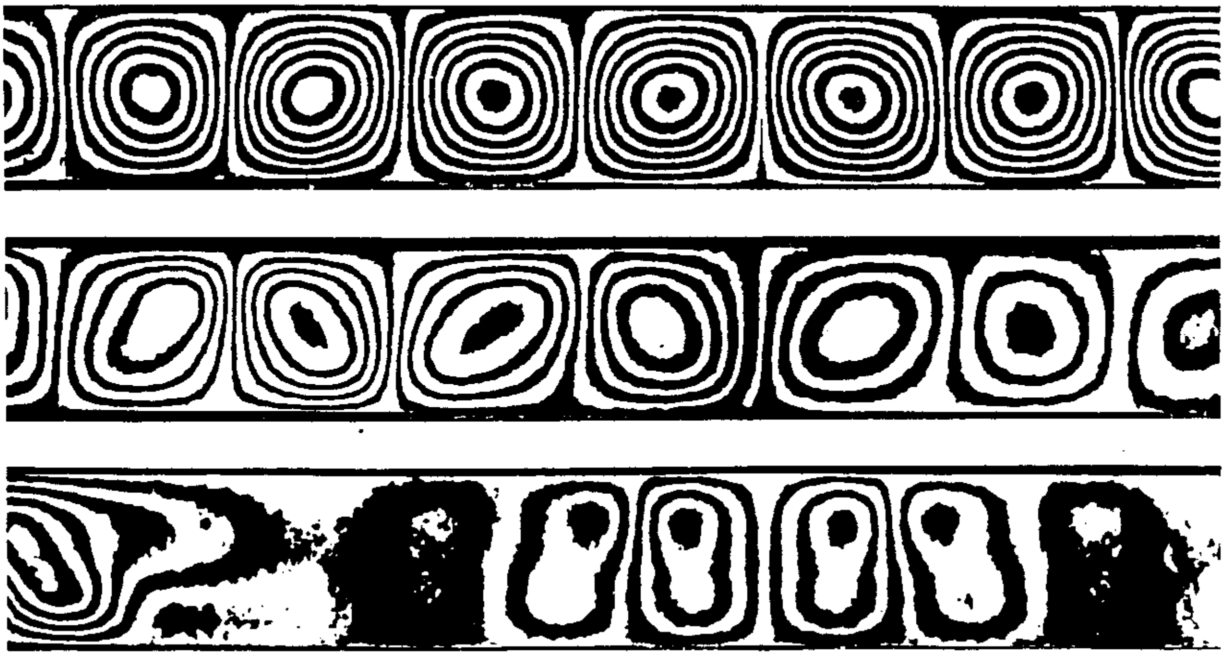


Fig. 11. A sideways view of convection cells in the laboratory. After fig. 142 in Van Dyke (1982) of experiments by Oertel and Kirchartz. From Oertel and Kirchartz (1979).

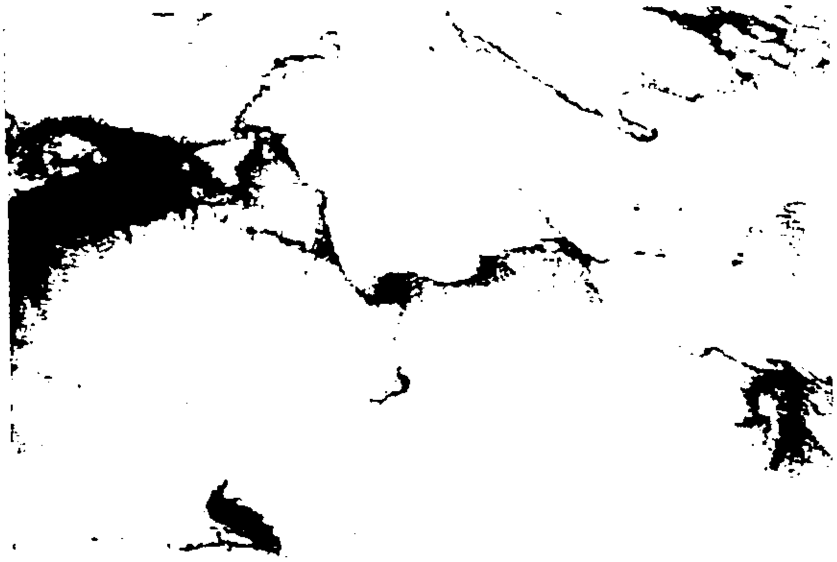


Fig. 12. Convection cells revealed by cloud tops. After fig. 7 in EdSC (1977).

years. Time runs forward down the left column and then down the right column. During the first half of the sequence, the "supercontinent" Pangea was being assembled, and during the second half, it was broken up until about 60 million years ago when the present Earth's surface map became recognizable.

NONLINEAR DYNAMICS: TURBULENCE, CHAOS, AND COHERENT STRUCTURES

The nature of geophysical fluid dynamics, the character of its flows and phenomena have been introduced and some processes illustrated. But geophysical fluid dynamics is

Fig. 13. Cumulus cloud puffs reveal convection pattern covering over all of Florida. After fig. 19 in EdSC (1977).

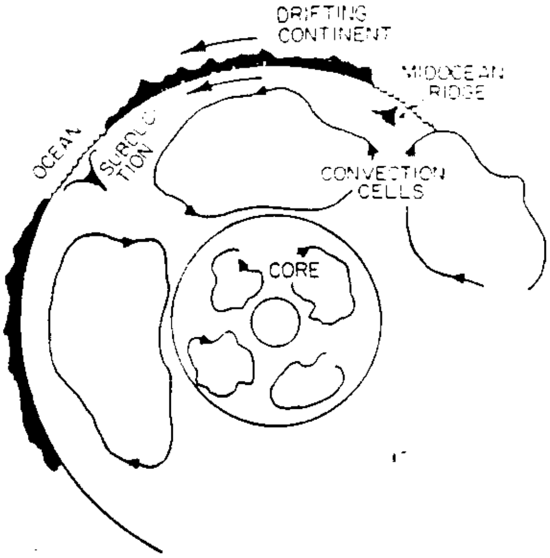


Fig. 14 Schematic convection patterns within the earth. R. Siever (pers. commun., 1988). See also Peltier (1985).

importantly a part of *modern fluid dynamics* which is itself contributing to the development of *nonlinear mechanics* generally. Contributions from geophysical fluid dynamics come from its methodology, from the experience of examples, and from the perspective provided by its unique scale.

There is a vast difference between linear physics (mechanics, or dynamics) and nonlinear physics. For the most part, the great triumphs of classical and twentieth century physics have dealt with linear phenomena. Linear dynamics involves some direct proportionalities such as response-to-forcing, and the ability to break down and add together directly components of a system with relative ease. These properties underly our ability to generalize, abstract and conceptualize. Nonlinear physical systems are notoriously difficult to deal with: what's happening just now in the system influences its response (that is, there are nonlinear feedbacks) and even solved examples provide frustratingly little insight for generalizations. Fluid dynamics is an essentially nonlinear branch of physics, and the problem of fluid turbulence resisted the attack of some of the same great physical minds that created quantum theory. However, we appear now to be at a subtle turning point in dealing with nonlinear fluid phenomena. Some general concepts are emerging which allow for a hopefully useful classification of nonlinear behaviours. *Turbulent flows* are partly deterministic and partly random. How and where in their description should this distinction be made? *Chaotic flows* are extremely complicated and never repeat themselves but are completely deterministic. Nonlinear processes can create order as well as disorder. *Coherent structure flows* are very long-lived stable vortices. We shall proceed to illustrate these concepts in turn.

Turbulent vortices larger than man himself naturally invite detailed investigation and deterministic physical studies. Examples are storms in the atmosphere and large ring vortices spun off by the Gulf Stream current in mid-ocean. The statistics of these events determine critical aspects of the general circulations. Fluid dynamicists generally now know that it is often relevant or necessary to study local dynamical processes of typical eddies even though only the average properties of the flow are of interest. Progress in understanding the turbulent boundary layer in pipes now involves the study of typical millimeter-scale vortices.

Let us look first at the Gulf Stream jet evolving and interacting with its field of ring vortices. I study the detailed local dynamics of this system with my group at Harvard, and we have begun to forecast them as the "internal weather of the sea". Our dynamical model is initialized with real ocean data, including satellite-observed sea surface temperature, which is shown for 2 March 1988 in Fig. 16. This is similar to Fig. 4 which showed the meandering stream and ring, but more typical a situation in that clouds cover most of the region. Useful information exists only in the western region. Note the humped shape just as the stream disappears behind the clouds. This shape is replicated on the upper panel of Fig. 17 at 38° N latitude between 70° and 72° W longitude. The maps show the coast-

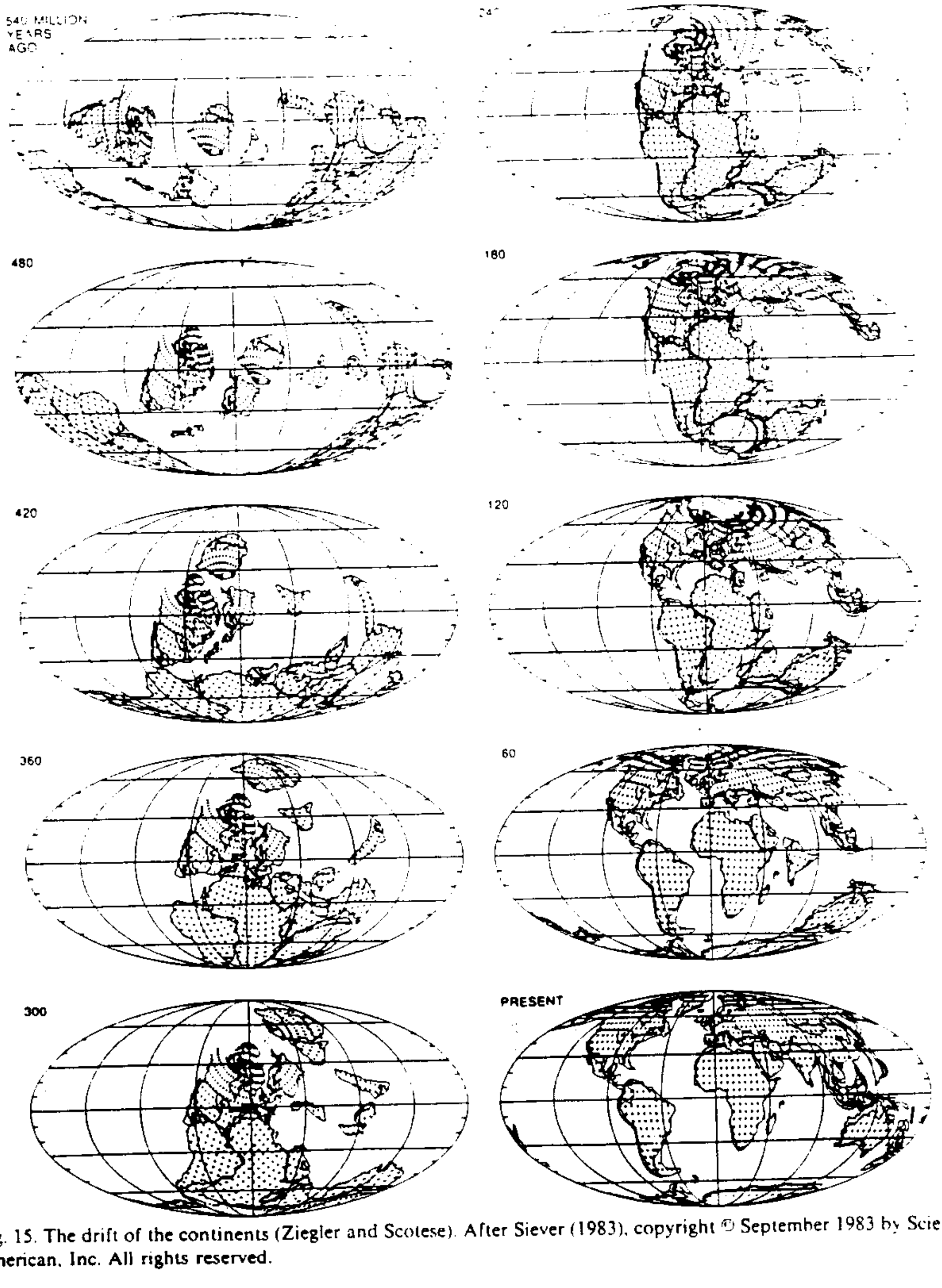
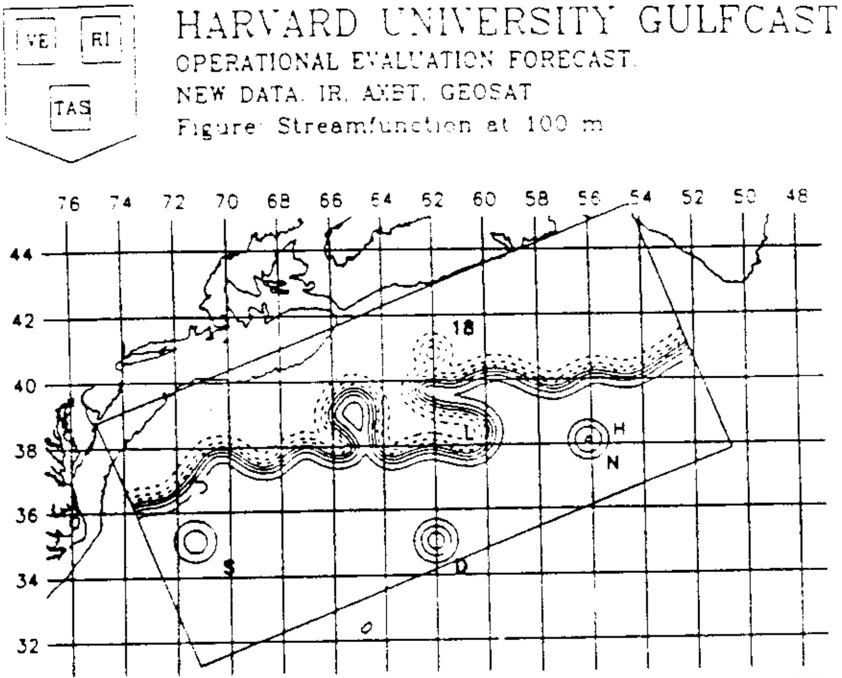


Fig. 15. The drift of the continents (Ziegler and Scotese). After Siever (1983), copyright © September 1983 by Scientific American, Inc. All rights reserved.



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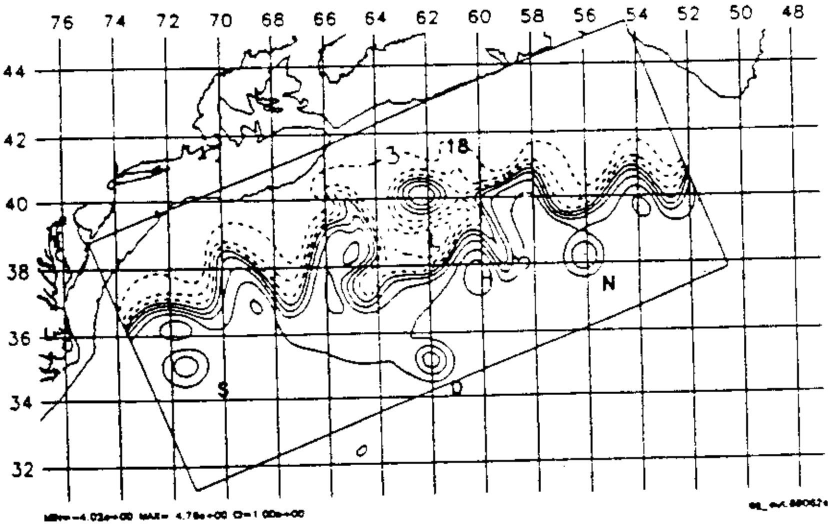


7 Day Forecast : 9 MAR 1988

Fig. 17. Gulf Stream jet and ring vortex, evolutions and interactions, 2–9 March, 1988 (Robinson and Glenn, 1988).

etc.. Generally, it is to be avoided. The question is, what causes the onset of turbulence? The organized flow on the right side of the picture actually consists of three types of features: a shear flow, waves (with wavefronts running from top to bottom) and "streamwise vortices" lying from right to left spiralling in the direction of the mean flow. The local dynamics of a "typical streamwise vortex" is just now known to hold the key to the puzzle of the onset of turbulence. Similar vortices are sketched schematically on Fig. 20. Note the shear flow profile: the turbulent patch in this instance would occur downstream or in the upper right corner. These vortices lie along the flow (in the x-direction)

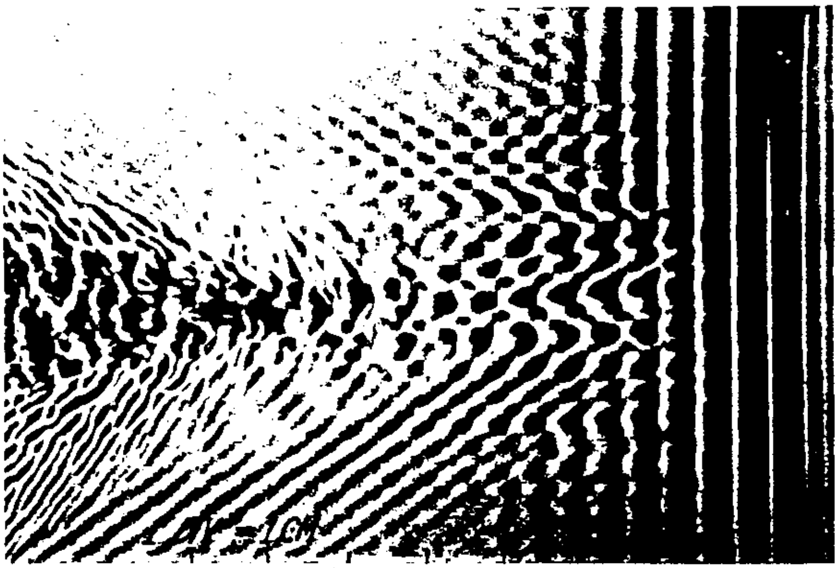


Fig. 19. Laminar shear waves leading to turbulence in a laboratory shear flow experiment, viewed from above (Suri and Abernathy, 1988).

phase space orbit and the top is a time series for one of the two variables involved (the horizontal or x-axis is time). The first system is dissipative: a constant value is approached in time and the system spirals into a point in phase space. The second system is simply periodic: one simple oscillation of the time series corresponds to once around the loop in phase space, and the system loops around forever. The third is multiply periodic but also loops around the same path forever. The last system is chaotic: it never repeats but occasionally jumps from loop to loop, or from one butterfly wing to the other. Actually, the orbit never touches itself again in three dimensions; it only appears to do so because of the two-dimensional projection. We see this in Fig. 27. The time series for one coordinate is repeated in the upper left corner. The upper right shows the orbit starting from a point and advancing in time, and the attractor itself is sketched in three dimensions. The relationship of these results to real weather phenomena raises interesting scientific and philosophical questions. Although deterministic, the chaotic system never repeats, jumps from wing to wing and can ebb sensitive to initial conditions. These characteristics relate to the important concept of a "limit of predictability" for the real atmosphere. Simply stated, all initial states contain small errors on scales smaller than the sampling grid. Nonlinear interactions in time inevitably transfer these

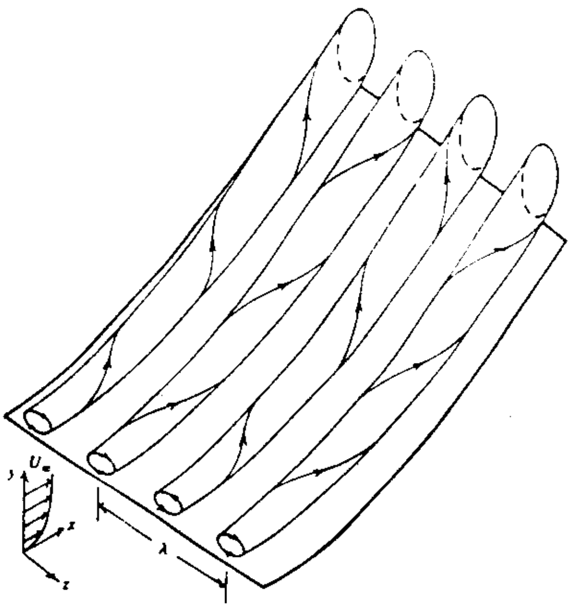


Fig. 20. Schematic of the typical streamwise vortices. After fig. 2 in Swearingen and Blackwelder (1987). Reprinted with the permission of Cambridge University Press.

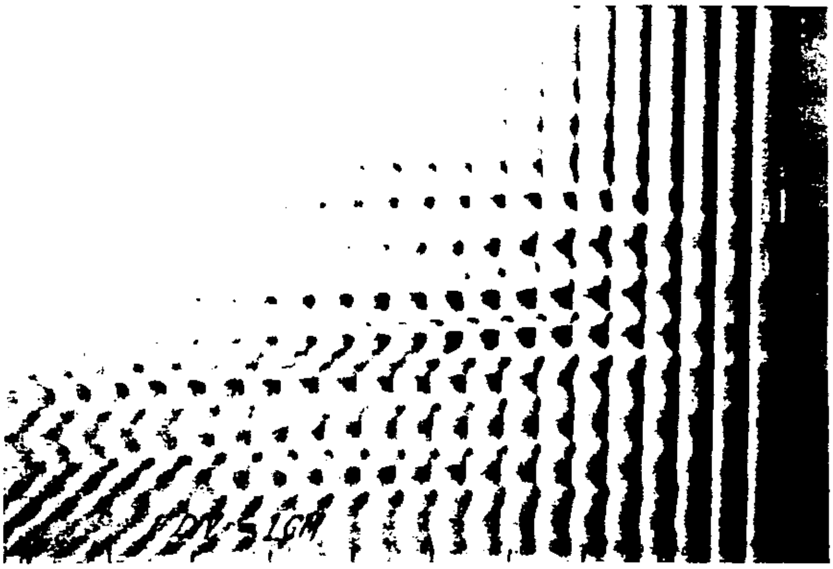


Fig. 21. Generation of streamwise vortices by shear waves in a laminar shear flow viewed with a strobe (Suri and Abernathy, 1988).

errors into the larger scales of interest and they gain energy. This happens in about two weeks for practical numerical weather prediction schemes and associated observational networks.

The nature of coherent structures and the research devoted to their study is exemplified by the Great Red Spot of Jupiter. This is seen on an actual photo from a spacecraft in Fig. 28a. The huge spot which is 1/3 the radius of the planet and known to exist for three hundred years looks red because it organizes the chemical composition of clouds locally. It is an anticyclonic spinning vortex in an anticyclonic planetary wind-shear zone which is part of Jupiter's general circulation. Fig. 28b is a modern laboratory rotating tank experiment. A large single stable vortex exists with

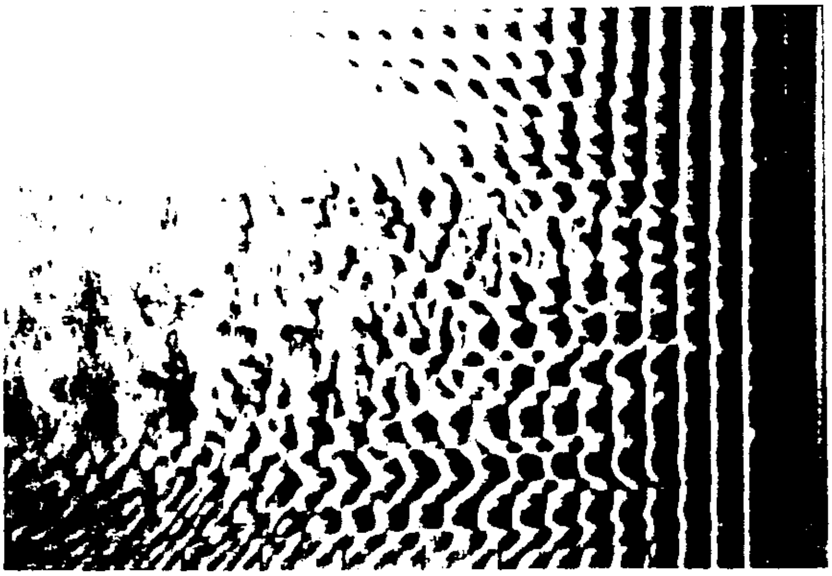


Fig. 22. The onset of turbulence caused by streamwise vortices as viewed with a strobe (Suri and Abernathy, 1988).

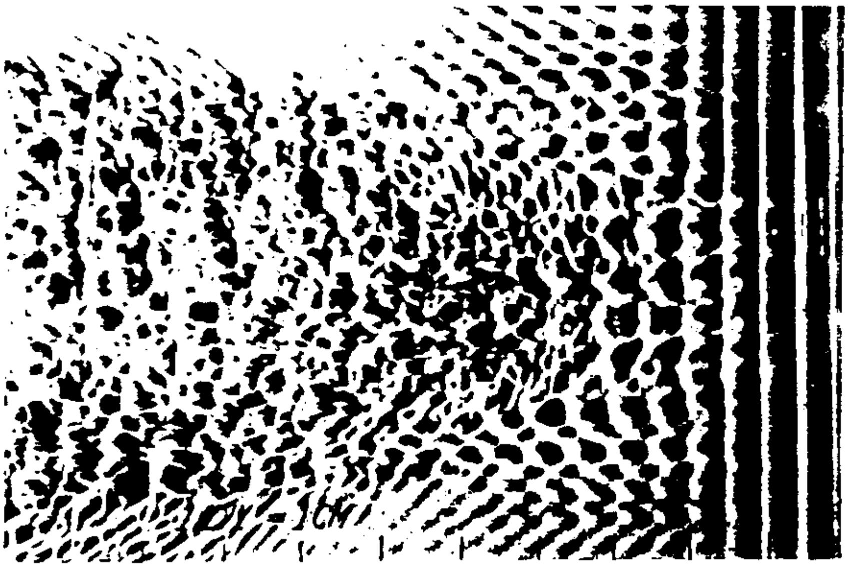


Fig. 23. The structure of a turbulent boundary layer, viewed from above. Turbulence, on the left, is generated by shear waves and streamwise vortices on the right (Suri and Abernathy, 1988).

the same relationship to the shear of the circulation in the jet in the tank, as the spot has to the planetary jet. Fluid pumped radially at the rim of the 30 cm rotating annulus created a jet which became unstable to five vortices which subsequently merged into the single coherent structure. It is interesting to remark that the laboratory experiment believed to relate to the nonlinear process which holds the Spot together was designed on the basis of a series of computer numerical experiments, themselves designed to study Spot dynamics. One such computer experiment is shown in Fig. 29. The time sequence of vorticity pictures advances from left to right and from top to bottom. What is depicted and coded by shading is the vorticity of spots relative to the vorticity of the background numerical jet shear. Two large spots are present initially. The darkest spot, surrounded by light gray, has the same vorticity as the jet, and the large medium dark spot is opposite signed vorticity. The medium spot streaks out filaments and fragments, but the red spot remains a stable vortex, a coherent structure for the duration of the experiment. A vorticity mechanism has been mentioned in the presentation of these laboratory and simulation process studies, but the basic message is simpler: nonlinear processes can in a range of important instances prevent dispersion and maintain isolated stable structures for very long times.

Fig. 24. Structure of the turbulent boundary layer viewed from the side. After fig. 162 in Van Dyke (1982) of an experiment by R.E. Falco.

SIMULATION: A NOVEL SCIENTIFIC METHODOLOGY

Computer experiments, or simulations, are playing a crucial role in the investigation of

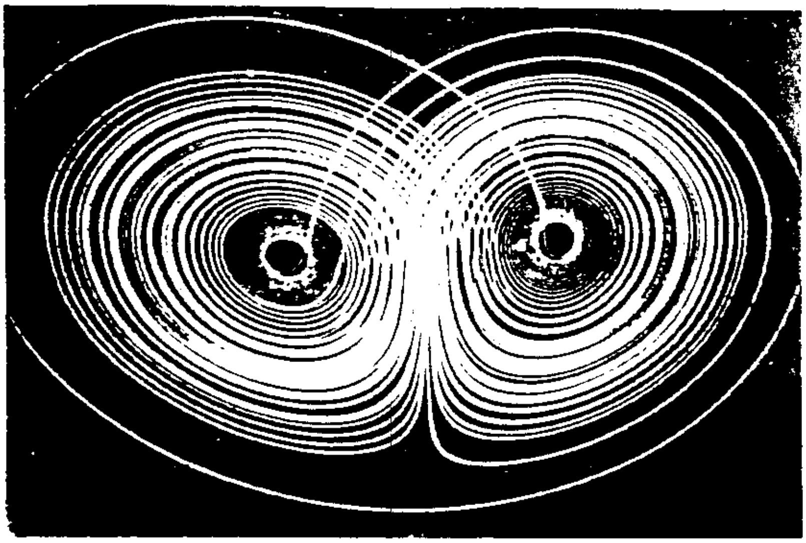
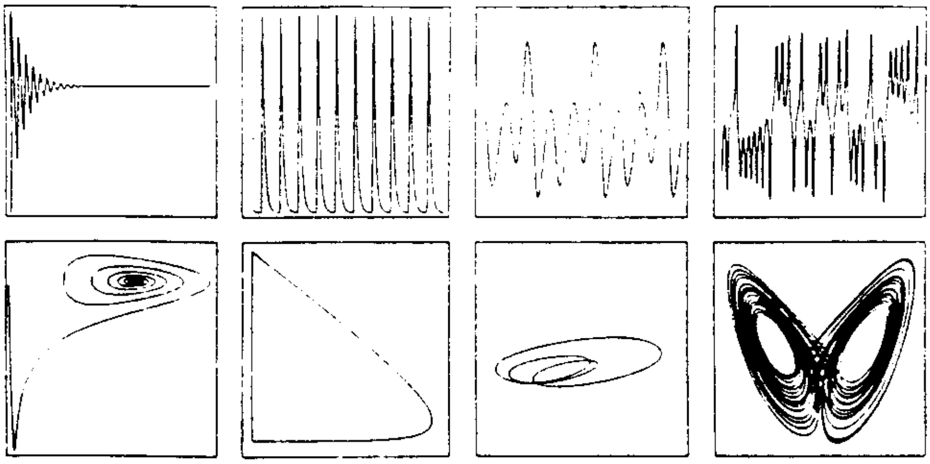


Fig. 25. The Lorenz attractor in phase space. After Gleick (1987). See also Lorenz (1963) and Thompson and Stewart (1986).

turbulence, chaos, and coherent structures. Geophysical fluid dynamicists have in fact been among forefront researchers in exploiting the steadily increasing speed and capacity of modern computers. Supercomputers today are powerful enough to allow realistic simulations of turbulent and planetary flows. A school of scientists and philosophers regard such simulations of computational physics as representing the first major advance in scientific methodology in centuries: scientific enterprise is now tripartite, with simulation on a par with theory and experimentation.

Ocean-circulation modelling exemplifies a subfield of geophysical fluid dynamics which needs the full power of today's and tomorrow's supercomputers and is fully ready to exploit their full power scientifically. The first numerical ocean models were run in the 1960's on computers one thousand times slower than today. What are the real requirements? Planetary-scale computations are required for



(a) (b) (c) (d)

Fig. 26. Time series (top) and associated phase space orbits for (a) dissipative, (b) simply periodic, (c) multiply periodic and (d) chaotic systems. After Gleick (1987). Reprinted by the kind permission of John Wiley and Sons, Ltd.

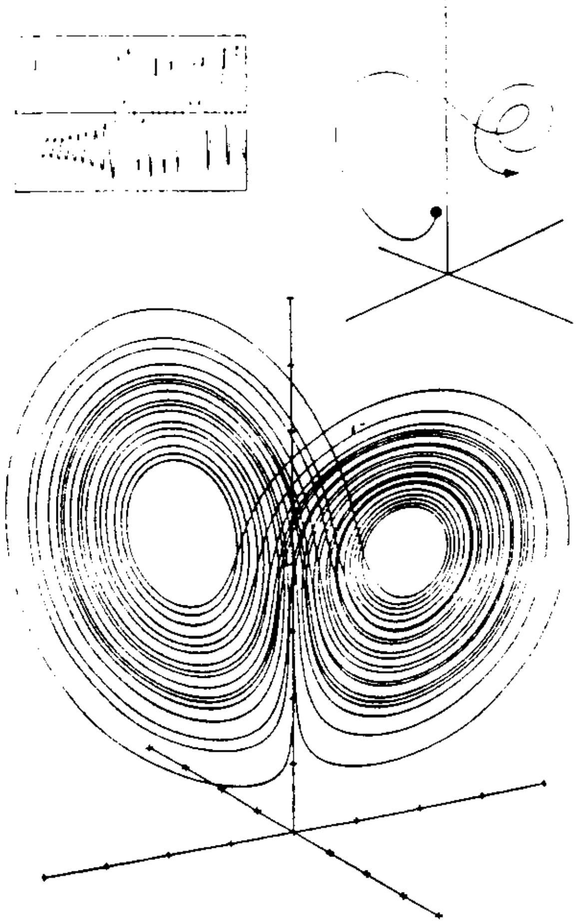


Fig. 27. The attractor in three dimensional phase space. After Gleick (1987). Reprinted by the kind permission of John Wiley & Sons, Ltd.

thousands of model years because of deep circulation turnover times and climate research. But the typical vortex whose local dynamics is critical has a radius of around 50 km. and other natural variabilities occur. Resolution requirements for a computational grid are 10 km horizontally, 100 m vertically, and a time step of less than an hour. This in turn requires hundreds or thousands of hours on today's supercomputers—for a single simulation experiment. But the nature of simulation research requires a matrix of related experiments to discover parametric dependencies and sensitivities to reveal processes. As always, ingenuity is required to exploit research resources. Here the answer is a hierarchy of multiscale models. Fig. 30 is a model of the Gulf Stream region extending from 25° to 50°N latitude and 40° to 80°W longitude. The resolution is 14 km. It is similar to the model of Fig. 17 used for detailed local dynamical studies. Note the very thin Gulf Stream jet and well defined ring. The next scale shown is a North Atlantic Basin model in Fig. 31 which extends from 15°S to 65°N latitude and 14°E to 100°W longitude. The 35 km resolution just resolves ocean eddies, but not so finely and accurately. Sea surface temperature is shown (dark is cold and light is warm). Note the narrow Gulf Stream leav-

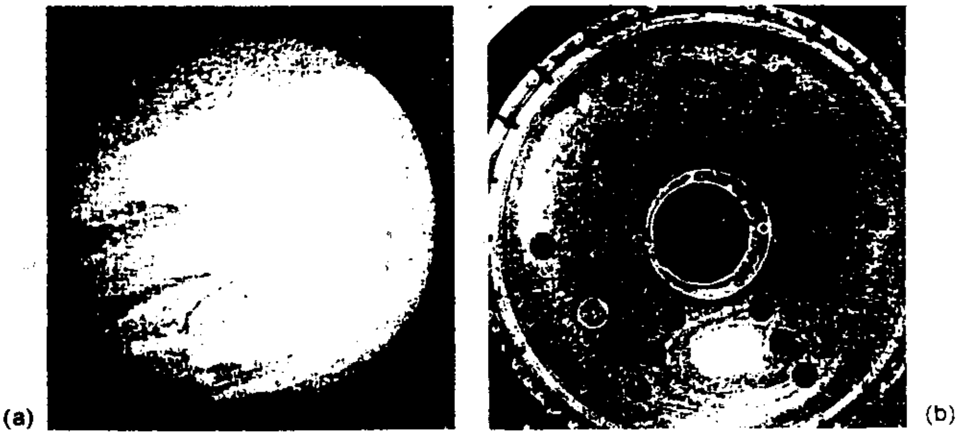


Fig. 28. The Great Red Spot of Jupiter. (a) photographed from a spacecraft and (b) a related laboratory experimental stable vortex. After fig. 1 in Ingersoll, 1988. (b) from Sommeria et al. (1988). Reprinted by permission from Nature. 331, copyright © 1988, MacMillan Magazines Ltd.

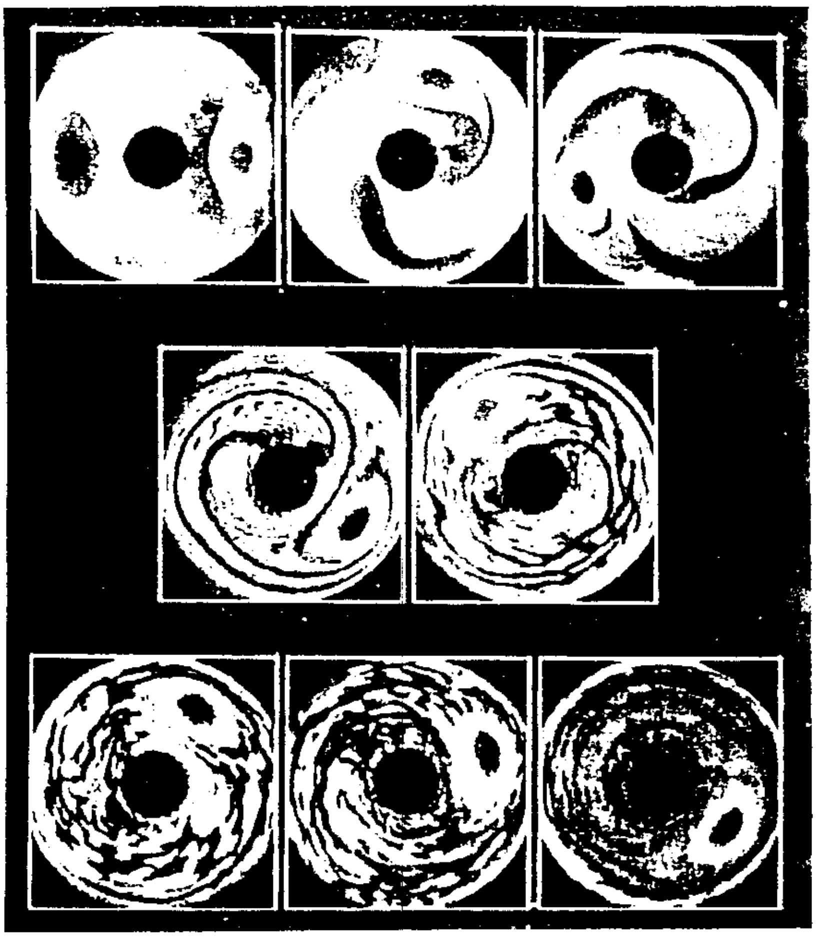


Fig. 29. A computer simulation of stable vortices. After Gleick (1987) from Marcus (1988).

ing the coast of North America, dispersing into the Northeastern Atlantic and warming the European coast with relatively warm "white" water. Fig. 32 shows the sea surface temperature from a global ocean model with 100 km resolution which no longer resolves the eddies. The generally zonal pattern of the observations of Fig. 5 is apparent. The Gulf Stream heat transport effect is more diffuse but present: note its counterpart by the Kuroshiu current which starts off Japan. Computer ocean models play a powerful role scientifically and also in the application of knowledge of currents and circulation to practical problems such as marine operations and planetary environmental management.

The complexity of nonlinear flows and the difficulty of acquiring data on planetary scales also naturally invokes ingenuity in estimating fields of interest. *Data assimilation* involves the continual blending of observational data with dynamical model output for the best overall representation of reality. The conceptual model of nature implied is novel.

INTERACTIVE PLANETARY RESEARCH: TOWARDS A WHOLE EARTH SYSTEM MODEL

Progress in geophysical fluid dynamics has advanced our knowledge of planetary processes and is allowing feasible research on interactive problems, such as the coupling between the atmosphere and the ocean and between the fluid earth and the biosphere (the complex terrestrial and marine ecosystems). Air–sea interactions control major aspects of

Fig. 30. Simulated sea surface temperature from a Gulf Stream Ocean model. After fig. 3 from Holland and McWilliams, 1987.

climate and the dynamics of climate change. The seasonal cycle is regarded as climate itself. Fig. 33 compares a model of the global surface temperature difference (August–February) (Fig. 33a) to observations. The model is a sophisticated atmospheric general circulation model to a simple ocean model. The patterns compare well; more sophisticated sets of coupled models are currently being researched. Year-to-year changes or

Fig. 31. Simulated sea surface temperature with a North Atlantic Ocean model. After fig. 2 from Holland and McWilliams, 1987.

Fig. 32. Simulated sea surface temperature with a Global Ocean model. After fig. 1 from Holland and McWilliams, 1987.

anomalies in the seasonal cycle occur. The El Niño/Southern Oscillation phenomena involves a dynamical coupling of the tropical ocean with the global atmosphere with aperiodic events causing profound biological and economic effects. For example, the 1982–83 El Niño caused severe floods or droughts in 12 countries, thousands of deaths and billions of dollars of damage. The richest anchovy fishery in the world, the Peruvian, dropped from 12 millions to less than 1 million metric tons. It is called El Niño (the Christ child) because the excessive warming of the waters off Peru occurs near Christmas. The process is schematized in Fig. 34. The normal situation is shown at top. Trade winds blow across the equatorial Pacific Ocean. Air rises and rain falls in the west. The thermocline, or boundary between cold and warm ocean water, rises to the east and cold water upwells off Peru. In an El Niño situation (bottom), the trade winds have reversed, air rises and rain falls in the east. The ocean surface has warmed, due to a lowering of sea level in the west and a plunging down of the thermocline off the Peruvian coast, so that warm water now upwells. These are the processes but we do not yet know what the essential nonlinear feedback mechanisms are. For example, do sea surface temperature changes essentially precede or follow wind changes? We do know that there are extensive effects in both the ocean and the atmosphere. Fig. 35 shows the anomalous sea surface temperature induced at mid-latitude off California in January 1983 (b) compared to an ordinary January 1982 (a). Clouds are white, dark is warm, cold is lighter. In the Santa Barbara channel entrance more than a 2°C change occurs and similar anomalies extend over large regions. Sea level was up by 20 cm along the entire coast, flooding occurred, anchovies disappeared and there was an invasion of red crabs. The global atmospheric response is shown in Fig. 36. Sketched are atmospheric pressure anomalies at sea level (Fig. 36b) and in the upper troposphere (Fig. 36a). There are high, polar effects. (The shaded region indicates enhanced rainfall and the arrows are anomalous surface winds.)

Research of the 1990's and the 21st century will involve the whole Earth system, with the fluid earth playing a critical role. Whole Earth system research is being considered now in order to describe, understand, simulate and predict on time scales of decades to centuries. A schematic of the whole Earth system is shown in Fig. 37. Winds, clouds, currents and sea-floor spreading are present, but also present are ice caps, atmospheric chemical processes, terrestrial photosynthesis, and the influence of human activity. The research

Fig. 34. Schematic of the El Niño Sc
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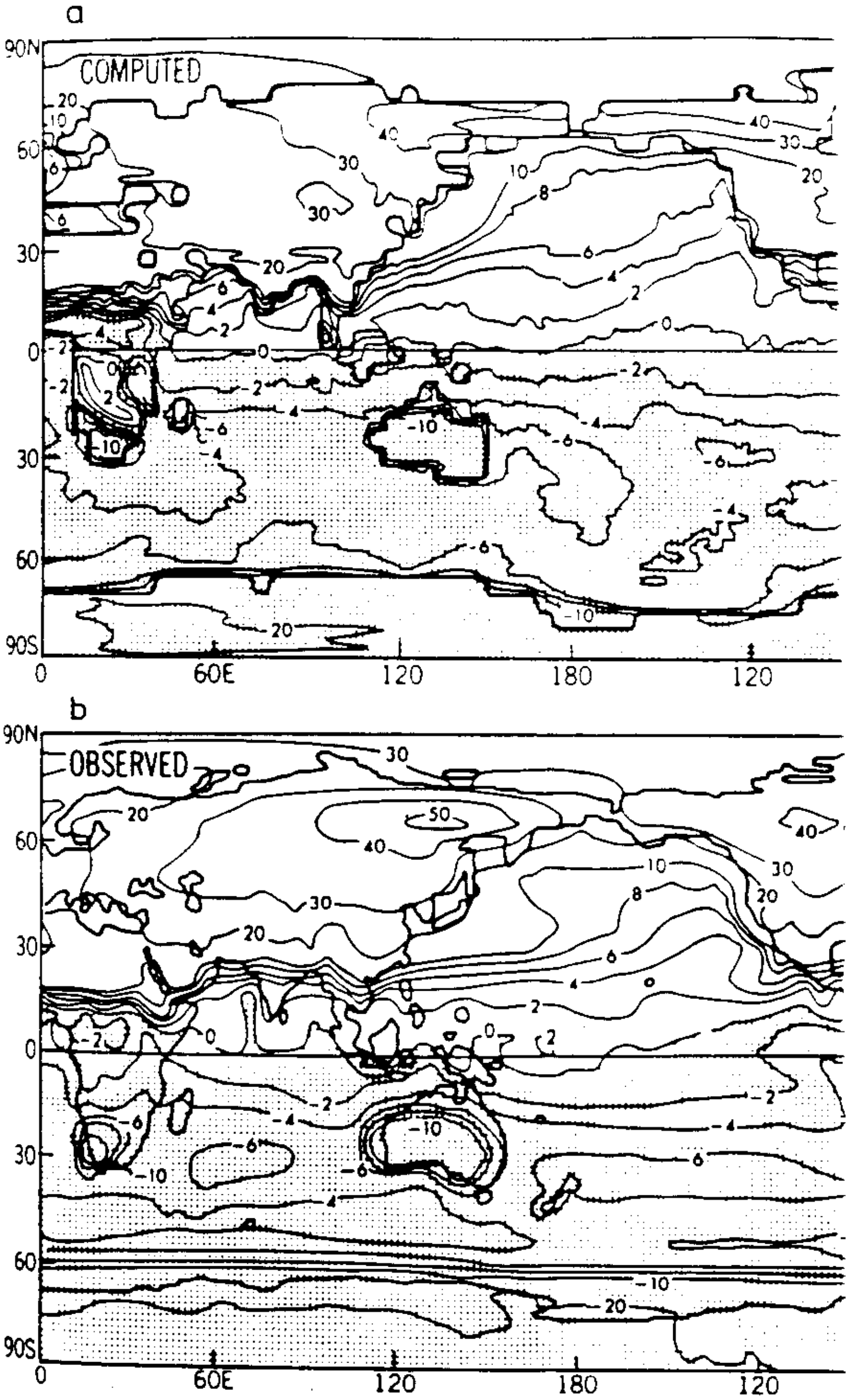

Fig. 33. Seasonal global surface temperature differences from (a) a global gen
observations. After fig. 7 from Manabe et al., 1979.

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frontier today makes feasable for the first time the coupling of the fluid Earth shown in Fig. 38 as the physical climate system, with

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Fig. 35. Sea surface temperature off California in (a) a typical January (1982) and (b) an El Niño induced anomalous January (1983) (NASA, 1984). Provided through the courtesy of the National Aeronautics and Space Administration, Washington, DC.

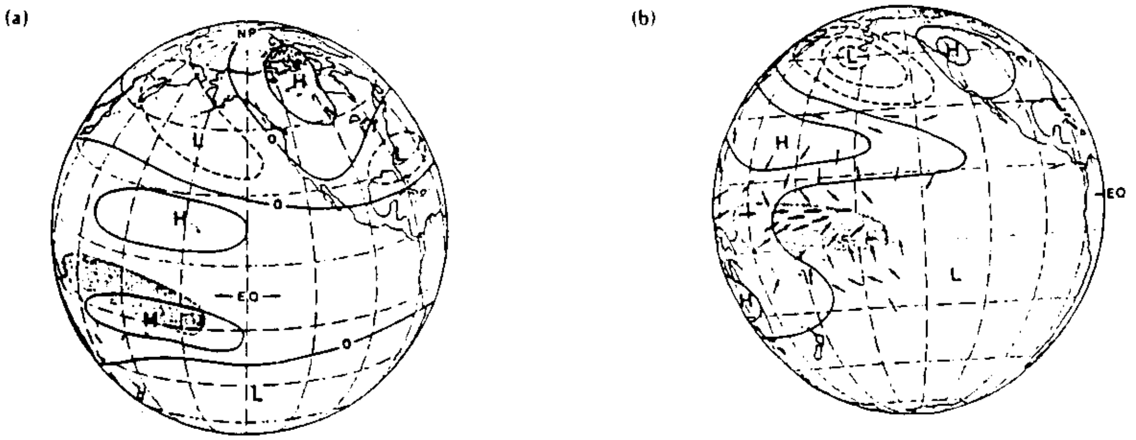

Fig. 36. Global atmospheric pressure patterns related to El Niño (a) in the upper troposphere and (b) at the surface. After fig. 4 in Rasmusson (1984).

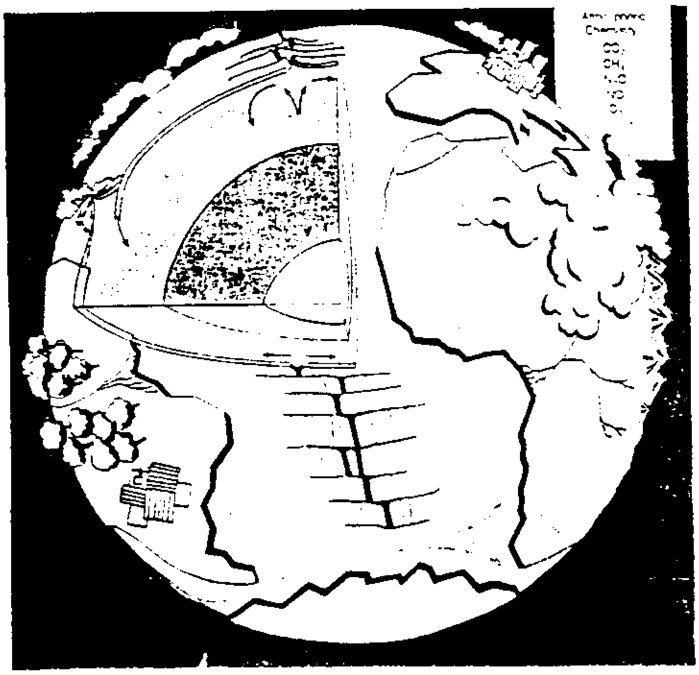

Fig. 37. Schematic of the whole Earth's system (Earth System Science Committee, NASA, Washington, DC, 1986). See also Malone and Roederer (1985).

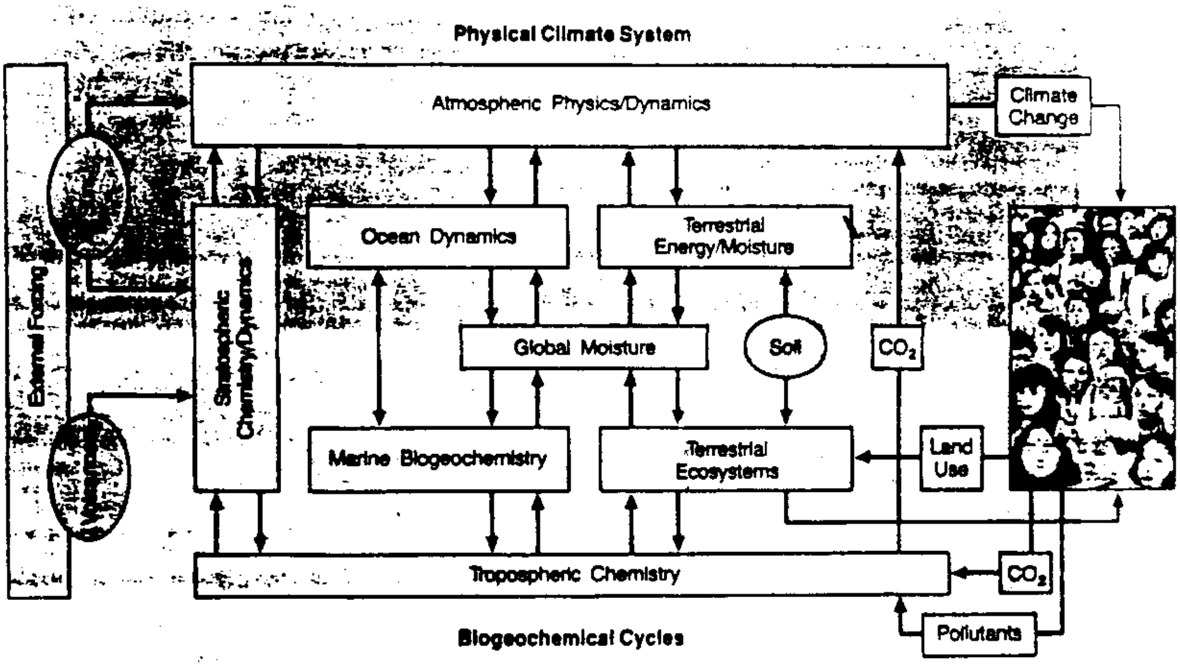

Fig. 38. Fluid and biological Earth processes (Earth System Science Committee, NASA, Washington, DC, 1986). See also IGBP (1987).

ship. Partial support was provided by the office of Naval Research under a contract to Harvard University for research on the Dynamics of Ocean Motions.

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*[1] This review is presented as an individual's overview of the field and the reference list is intended only to identify source material for illustrations and to provide an introduction into topical literature sources.