

## JOINT COLLOQUIA

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## METEOROLOGICAL MODEL EXPERIMENTS\*

by Paul Frenzen<sup>‡</sup>

Dr. Frenzen of the Radiological Physics Division, Argonne National Laboratory, Argonne, Illinois, U. S. A., commenced his talk with the observation that throughout the past hundred years or more, meteorological model experiments seem to have been revived every two or three decades. The current such revival, begun in the United States by the work of D. Fultz at the University of Chicago shortly after World War II, has, however, shown every sign of being a lasting one. This probably stems, more than any other single factor, from the introduction of dynamical similarity principles, an approach which successfully elevates meteorological models from their earlier status of mere laboratory demonstrations.

In 1946 the staff of the Department of Meteorology at Chicago under the inspired direction of the late C. G. Rossby carried out a series of parallel investigations on the consequences to the general circulation of large scale lateral mixing in middle latitudes. One of these studies (originally, in fact, suggested by Rossby) was an experimental laboratory model, a rotating hemispherical shell of water within which jet-like distributions of zonal circulation were found to form as a result of meridional mixing generated by heating at the pole. Subsequent to this promising beginning, Fultz and his co-workers went on to develop the rotating cylinder apparatus which has since become widely known as "the dishpan experiment", a name that recognizes the prosaic origin of the container within which the experiment was first performed.

Before coming to the highly baroclinic and surprisingly realistic "dishpan", it will be of interest to describe two related but somewhat simpler models of large scale circulations, also developed at Chicago. In one of these the fluid remains completely homogeneous (i. e., the density is constant), while in the other the entire density gradient is concentrated in a single interface between two fluids.

For the homogeneous fluid model, a rotating hemispherical shell similar to that used in the original heating experiment was arranged to continuously drive fluid over or around obstacles which thus became, in effect, analogues of large scale mountain barriers on the earth. The experiment showed that, whereas relative westerly flow past such obstacles would generate a train of long waves downstream (due to the conservation of potential vorticity in fluid columns forced to change either their vertical dimensions or their latitude), relative easterly flow past the same barriers could not. The lengths of the long waves in the westerlies were observed to depend solely upon the Rossby number, a ratio between the relative velocity of the mean current and the absolute velocity of a point on the equator. The relationship was found to correspond closely with a frequency equation for planetary waves originally given by Haurwitz.

The sequence of events observed during wave number changes in the obstacle experiment, suggests an association between the occurrence of an eccentric circumpolar vortex with periods of maximum zonal circulation as a result of the presence of large mountain barriers on the earth. Thus, the model admits of a condition in which the zonal flow is of sufficient strength to generate a single wave in the lee of a barrier, but not yet strong enough to move the vortex into a position of symmetry, directly across the pole from the obstacle. The pattern then essentially consists of an eccentric vortex whose centre of circulation no longer coincides with the geographic pole; in the experiment, the new pole locates near a meridian one hundred degrees downstream from the longitude of the obstacle. There is some evidence to suggest that

\* Talk accompanied by motion pictures supplied by Professor D. Fultz, Hydrodynamics Laboratory, Department of Geophysical Sciences, the University of Chicago.

‡ Dr. Frenzen was currently visiting the Division of Meteorological Physics, C. S. I. R. O., Aspendale, Victoria.

such an effect occurs in the northern hemisphere as a result of strong zonal flow past the Himalayan massif, and it is of interest to speculate upon the possible consequences to the southern hemisphere circulation that might similarly be affected by the presence of the Andes.

The second experiment consists of a rotating cylinder containing two immiscible fluids overlying one another, the relative difference in their densities being but a fraction of one percent. After this system has been brought to solid rotation at a moderately high rate, a rapid reduction in the angular velocity of the container to some constant slower rate causes the lower liquid to decelerate more rapidly than the upper; the resultant reduction in centrifugal forces in the lower layers (in comparison to the relatively undisturbed pressure field primarily associated with the fluid layers above) causes the denser liquid to draw together into what amounts to a highly simplified analogue of the dome of colder air that occupies each polar region of the earth's atmosphere.

At the outer edge of the dome, the circumstances of the experiment combine to furnish all the requisites for a classical Margulian frontal surface: the system features a sloping density discontinuity supported by pressure gradient and Coriolis forces that result from the simultaneous presence of cyclonic shear and a basic rotation. What is more, provided certain conditions of density difference, shear strength, and rotation rate are suitably met, the frontal model thus produced will be dynamically unstable; the edge of the interfacial dome will undergo a series of progressive, wave-like distortions which individually evolve in the manner specified by the Solberg-Bjerknes wave cyclone theory. And, most interestingly, relative motions of small tracer particles floating on the free surface of the upper liquid reveal the presence of a jet-stream, a virtually continuous current of higher velocity flow meandering through patterns of troughs and ridges aloft, precisely in phase with surface frontal wave developments below.

The principal model devised at Chicago, namely the dishpan experiment, consists of a shallow, rotating cylinder of water, uniformly heated at the outer wall and uniformly cooled at the centre, the last either through a region of the bottom at the pole or through the walls of a small, inner cylinder centred in the same position. With these energy sources arranged to maintain a constant temperature difference between the centre and the wall, rotating the cylinder slowly results in the onset of a symmetrical "Hadley" circulation; streams of ink introduced at several levels reveal easterly "trade winds" diverging from the pole in the lower layers, while the upper levels feature westerly "counter trades" that converge poleward. The pattern is strongly suggestive of that observed in the atmosphere in tropical latitudes where, it will be noted, the horizontal component of the earth's rotational influence is also small.

Increasing the rate of the cylinder's rotation causes the circulation to enter the "Rossby regime", a meteorologically realistic state featuring jet-streams, troughs, and ridges aloft which, as in the case of the simpler two-liquid model, can be seen to be associated with typical surface frontal systems in the lower layers. The presence of a cylindrical heat sink in the centre of the dishpan exerts a strongly stabilizing influence upon the Rossby regime, the circulations in this case assuming the character of quasi-permanent trains of long waves extending around the globe in middle latitudes. When, however, a heat sink at the bottom is substituted and the central constraint is thus removed, the circulations are free to evolve quite realistically, generating split jets, cut-off lows, blocking highs, etc. in a manner remarkably similar to that exhibited by the upper troposphere in middle latitudes.

The dishpan experiments reveal the interesting fact that, in order to duplicate virtually every significant feature of the general circulation of the atmosphere, a fluid system need only be subject to the forces generated by a basic rotation and a horizontal temperature gradient; variations in the lower boundary such as those which typify the surface of the earth are not required. In addition, certain conditions of heating and rotation in even this rudimentary model have been found to generate relatively long-term, low-order instabilities which compare favourably with the known characteristics of the atmospheric index cycle. The circulation "vacillates" between alternate states of excessive and deficient meridional exchange, either condition inevitably leading to the other since the constant energy input would require some intermediate transfer rate to maintain a steady state. In this "vacillation" regime, entire trains of long waves can be seen to pass through a regular cycle of intensification along north-south (i. e. radial) trough lines, followed by a slight tilting in the negative direction that

just precedes the formation of cut-off upper cyclones; cyclones thus produced elongate along positively tilted axes and proceed to re-establish the pattern of open waves by opening their poleward sides; the waves subsequently re-align themselves along radii and the sequence begins again.

Finally, it can be said that although meteorological model experiments will, in themselves, probably never produce weather forecasts, they do enable complex atmospheric circulation phenomena to be recast in sufficiently simple form for an observer to see the basic problem. In this, their essentially rudimentary nature is a distinct asset; for they strip a system of all but its bare essentials, and thus often clearly indicate the way to a solution.

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## DISCUSSION

The speaker initiated discussion by inviting comments on a correlation which he considered might occur between latitude and the intensity of the jet maxima over eastern Australia, and also on his hypothesis that the winter anticyclone over the South Atlantic was of relatively great intensity.

DR. U. RADOK believed that recent work by Dr. Schwertfeger had failed to reveal any great intensity in the trough east of the Andes and he thought this tended to discount the likelihood of intense anticyclonic characteristics downstream.

MR. G. T. RUTHERFORD on the same point stated that this area was outside the sphere of the Australian Analysis Office but that on a lesser scale some corollary might be drawn from the South African and Indian Ocean area. In his experience there was a semi-permanent trough east of South Africa, particularly in winter, but strong intensity of the downstream high was not a recognized feature. On the second point he stated that no obvious

correlation had been noted possibly because of the limited latitudinal range of the network. However, very strong jets in excess of 200 kt had been noted at relatively low latitudes and in particular a recent case with an observed wind over 270 kt from a station at about 35°S. These cases did not seem to fit readily into a pattern prescribing strongest jets at high latitudes.

MR. J. N. McRAE stated that, when completed, a project\* currently under investigation by A. J. Muffatti of the Bureau would probably answer Dr. Frenzen's query regarding the latitude dependence of the intensity of jet streams over eastern Australia.

DR. FRENZEN (the speaker) replying to a question by Mr. Clarke said that Dr. Fultz believed that the unstable two-wave flow in the "dishpan" has some relevance to the sudden stratospheric warming observed in the Arctic circle in February and that possibly this applies also to that observed in the Antarctic circle in October.

It may be that in the mid-winter stratosphere the circulation around the polar vortex is strong enough to support a one wave perturbation. The weakening of the circulation in late winter or spring (the difference between the hemispheres should be instructive) makes possible a two wave system, which, at least in Arctic regions, behaves somewhat similarly to that in the "dishpan". The anticyclone appears to push a ridge through to the pole, breaking the elongated two-wave flow pattern into two cyclonic vortices.

MR. R. H. CLARKE said that in Antarctica less information is available, but it cannot be said so far that the process is similar there. An amplifying one-wave pattern appears to be responsible for the "high" replacing the "low" in the polar stratosphere. (C. E. Palmer and R. C. Taylor, 1960: Journal of Geophysical Research, 65,3319). Sudden temperature rises occur as a result of descending motion accompanying the replacement process.

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#### AGROMETEOROLOGY IN U. K. AND EUROPE

by C. E. Hounam

Mr. C. E. Hounam of the Bureau of Meteorology, who had recently made an extensive study tour of Agrometeorological establishments in the United Kingdom and Europe, expressed the opinion that there was not much interest in the measurement of evaporation from tanks but interest in estimating evaporation is fairly widespread, particularly in the U. K. The Meteorological Office plays a leading part in irrigation prediction services but other useful contributions are carried out by some Universities and other authorities. In West Germany an irrigation service is based on an equation developed by Haude using the saturation vapour pressure deficit of the air and a crop factor. By contrast, a well equipped station exists in Denmark using both small and large evaporimeters and data from small (1/3 sq. metre) tanks are used in predicting irrigation requirements.

Soil moisture measurements are made fairly generally but techniques vary. Various types of porous block and elements such as stainless steel-nylon are used, but of interest were two more approximate methods used in Germany for field use. One mixed calcium carbide with the weighed soil sample in a cylinder and a pressure gauge observation was calibrated to give moisture content. In another method the soil sample was weighed, wetted with alcohol and fired, then reweighed.

Lysimeters are used in most countries but designs have not been standardized. The Morris balance at Silsoe, referred to at a Colloquium in September 1962, is an outstanding instrument which has been duplicated at several sites in England and at two C. S. I. R. O.

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