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Studies of residence times of chlorofluorocarbons using a two-dimensional model

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Summary

In order to predict the possible effects of chlorofluorocarbons (CFCs) on stratospheric ozone, it is necessary first to gain an understanding of the movement of these substances in the atmosphere and their likely speed of removal. It is this preliminary project which is reported in this paper. The computations covered several decades of model-time up to the present, and were continued in order to estimate the lifetimes of CFCs in the atmosphere under differing conditions.

1. Introduction

There has been considerable discussion in recent years about the possible effects of chlorofluorocarbons (CFCs) on the ozone layer in the stratosphere (Lovelock *et al.* 1973, Molina and Rowland 1974, IMOS 1975, Department of the Environment 1976, National Academy of Sciences 1976). An important aspect of the problem is that the CFCs released into the troposphere are apparently not greatly depleted in this region of the atmosphere. Their major sink if this hypothesis is correct is photolysis by solar ultra-violet radiation after transport upwards into the stratosphere. Studies using one-dimensional models have indicated that this is a very slow process, and even if releases at the surface were stopped, CFCs accumulated in the tropospheric reservoir would continue to diffuse upwards and continue to cause ozone depletion for many decades or even centuries. Questions of the distribution with latitude and the transfer between hemispheres are of considerable importance because the major source of these substances is in the northern hemisphere and any sinks will be more widely distributed over the globe.

In order to gain further understanding of the spread of these substances in the atmosphere, computations were performed with a two-dimensional model to simulate the transport and photochemical destruction of chlorofluorocarbons F11 ($CFCl_3$) and F12 (CF_2Cl_2). The computations covered several decades of model-time up to the present, and were continued in order to estimate the lifetime of CFCs in the atmosphere under differing conditions of surface release. Calculations were made with and without the effects of chemical and photolytic destruction for both F11 and F12, and also with and without a simulation of surface deposition or removal. This particular study was confined to the CFCs themselves; the resultant effects on other atmospheric constituents (particularly ozone) were not included at this stage.

2. Description of the model and the chlorofluorocarbon injection

The two-dimensional model has a latitude–pressure grid. In the horizontal there are 12 intervals with a spacing of 15 degrees of latitude (82·5°N to 82·5°S), and in the vertical there are 23 levels with an interval of 0·3 in $\log_e$ pressure (1 mb to 735·1 mb) corresponding to a spacing of about 2 km, above a lowest layer centred at 930·2 mb with a surface pressure of 1013·2 mb. The effects of photochemistry were ignored in the lowest four layers, which were assumed to be entirely within the troposphere.

The annual releases of CFCs F11 and F12 for the years 1931–75 were taken from figures published by the Manufacturing Chemists Association (1976) and are shown in Table I. It was assumed that the 1975 values applied also to 1976–78 and thereafter experiments were run with differing conditions of surface release. The releases for the United States of America were assigned to 37·5°N and those for the rest of the world to 52·5°N, the relative proportions being derived from Table VI–7 of IMOS (1975).

The model is based on the two-dimensional continuity equation for each chemical (described in section 3) integrated for both the dynamics and the chemistry. A forward time-step of two hours was used in the dynamics, the transport parameters being altered every 24 hours. Injections at the surface were also made every two hours. The chemical destruction rates were computed separately every 10 minutes, 12 chemical time-steps being performed between each dynamical time-step. Centred differences were used for computing derivatives in space.

3. The dynamics and the redistribution by transport

From continuity we can write the equation for the rate of change of volume mixing ratio, χ, of an atmospheric constituent as

$$\frac{\partial \chi}{\partial t} = -\frac{1}{E\cos\phi}\frac{\partial}{\partial \lambda}(u\chi) - \frac{1}{E\cos\phi}\frac{\partial}{\partial \phi}(v\chi\cos\phi) - \frac{\partial}{\partial p}(\omega\chi) + S, \qquad \text{(1)}$$

where E is the radius of the earth

ϕ, λ are latitude, longitude

u,v are zonal, meridional velocity

p is pressure

ω is dp/dt

S is net source and sink term.

For any variable, x, we take the average, $\bar{x}$, round a latitude circle to be given by

$$\bar{x} = \frac{1}{2\pi}\int_0^{2\pi} x\, d\lambda \qquad \text{(2)}$$

and x', the deviation of x with longitude, as $x' = x - \bar{x}$.

Equation (1) thus reduces to

$$\frac{\partial \bar{\chi}}{\partial t} + \frac{1}{E\cos\phi}\frac{\partial}{\partial \phi}(\overline{v\chi}\cos\phi) + \frac{\partial}{\partial p}(\overline{\omega\chi}) = \bar{S} \qquad \text{(3)}$$

But $\overline{v\chi} = \bar{v}\bar{\chi} + \overline{v'\chi'}$ and $\overline{\omega\chi} = \bar{\omega}\bar{\chi} + \overline{\omega'\chi'}$.

Reed and German (1965) give the eddy fluxes in terms of eddy diffusion coefficients in the form

$$\overline{v'\chi'} = -\left(K_{yy}\frac{\partial \bar{\chi}}{\partial y} + K_{yz}\frac{\partial \bar{\chi}}{\partial z}\right) \qquad (4)$$

$$\overline{w'\chi'} = -\left(K_{zy}\frac{\partial \bar{\chi}}{\partial y} + K_{zz}\frac{\partial \bar{\chi}}{\partial z}\right), \qquad (5)$$

Table I. *Releases of* F11 *and* F12 *in millions of pounds**

	F11		F12	
Year	US sources	Other sources	US sources	Other sources
1931	0·0	0·0	0·1	0·0
1932	0·0	0·0	0·1	0·0
1933	0·0	0·0	0·2	0·0
1934	0·0	0·0	0·3	0·0
1935	0·0	0·0	0·5	0·0
1936	0·0	0·0	0·8	0·0
1937	0·1	0·0	1·3	0·0
1938	0·1	0·0	1·9	0·0
1939	0·1	0·0	2·8	0·0
1940	0·2	0·0	3·8	0·0
1941	0·2	0·0	5·1	0·0
1942	0·3	0·0	6·3	0·0
1943	0·4	0·0	7·8	0·0
1944	0·5	0·0	10·4	0·0
1945	0·6	0·0	13·6	0·0
1946	1·4	0·0	26·3	0·0
1947	2·7	0·0	41·9	0·0
1948	5·0	0·0	49·0	0·0
1949	8·2	0·0	53·3	0·0
1950	11·9	0·0	59·7	0·0
1951	16·5	0·0	66·5	0·0
1952	23·8	0·0	69·5	0·0
1953	32·4	0·0	78·3	0·0
1954	40·2	0·0	88·8	0·0
1955	49·9	0·0	100·5	0·0
1956	62·3	0·0	116·4	0·0
1957	69·8	0·0	132·5	0·0
1958	65·7	0·0	138·7	0·0
1959	67·2	0·0	154·8	0·0
1960	71·3	16·8	161·1	24·3
1961	90·4	22·8	173·3	35·1
1962	111·6	30·6	192·9	47·5
1963	132·7	41·7	216·6	66·9
1964	148·6	58·2	240·2	91·6
1965	163·8	73·2	265·0	111·5
1966	167·1	96·4	282·2	144·1
1967	180·5	123·9	303·7	183·2
1968	193·9	152·1	307·2	225·2
1969	221·7	181·9	333·7	265·7
1970	235·2	225·5	337·6	315·0
1971	248·1	263·4	339·9	358·2
1972	275·1	300·7	363·1	406·9
1973	313·6	352·2	397·3	446·2
1974	353·9	397·5	439·9	494·1
1975	353·6	397·2	428·9	481·7

* One million pounds = 453·6 tonnes.

where w is vertical velocity and z is height. Changing to pressure co-ordinates and using the approximations $K_{yz} = K_{zy}$, $K_{yp} = -g\rho K_{yz}$ and $K_{pp} = g^2\rho^2 K_{zz}$, where ρ is density, equations (4) and (5) are then replaced by

$$\overline{v'\chi'} = -\left(K_{yy}\frac{\partial\bar{\chi}}{\partial y} + K_{yp}\frac{\partial\bar{\chi}}{\partial p}\right) \qquad (6)$$

$$\overline{\omega'\chi'} = -\left(K_{yp}\frac{\partial\bar{\chi}}{\partial y} + K_{pp}\frac{\partial\bar{\chi}}{\partial p}\right) \qquad (7)$$

where $\delta y = E\delta\phi$.

Values of $\bar{v}$ for each season were estimated using the values of Newell *et al.* (1972) up to 10 mb in the northern hemisphere and 100 mb in the southern hemisphere. These were extended upwards subjectively using as guidance mean cross-sections of $\bar{v}$ from the COMESA (1975) three-dimensional model and also output from the two-dimensional model of Harwood and Pyle (1975). Mean vertical velocities, $\bar{\omega}$, were calculated from $\bar{v}$ using the continuity equation

$$\frac{1}{E\cos\phi}\frac{\partial}{\partial\phi}(\bar{v}\cos\phi) + \frac{\partial}{\partial p}\bar{\omega} = 0 \qquad (8)$$

with $\bar{\omega} = 0$ at the top of the model. In order to ensure that $\bar{\omega} = 0$ also at the surface, a small correction was applied to $\bar{v}$ at all levels, to make the integral of $\bar{v}dp$ zero at the junction between each latitudinal column. Also $\bar{v}$ was zero above each pole. Schematic diagrams of the corresponding stream functions are shown in Figures 1(a)–(d).

Values given by Luther (1974) were taken as a basis for the eddy diffusion coefficients, those for the southern hemisphere being obtained by using northern hemisphere values for the corresponding season. However, a study of the COMESA three-dimensional model indicated that during stratospheric sudden warmings the variances of the meridional velocity may greatly exceed those given by Newell *et al.* (1966) which were used by Luther in obtaining his results. (Reed and German (1965) suggest that eddy diffusion coefficients K_{yy} are proportional to the variance of the meridional velocity.) Also the three-dimensional model results indicated that in the southern hemisphere winter the variance of the meridional velocity is less at high latitudes than in the northern hemisphere winter. Subjective changes were made to Luther's coefficients, in the light of available information, and then tested on the version with full chemistry of the two-dimensional model. The improved simulation of natural ozone was taken as confirmation that these changes should be incorporated. In the northern hemisphere climatological temperatures were used, those for the southern hemisphere being taken from the northern hemisphere at the corresponding season.

In order to obtain daily values a sinusoidal variation between solstices was assumed for the eddy diffusion coefficients and the temperatures, the phase of the former being delayed by one month. For the mean velocity components, a piecewise smooth quadratic function was interpolated between seasonal values.

4. The destruction mechanisms

The only source of CFCs in the model is the injection into the lowest layer, whereas three possible destruction mechanisms have been included, namely 'surface deposition', photochemical dissociation by solar ultra-violet radiation in the stratosphere, and chemical reaction with $O(^1D)$* in the stratosphere.

* $O(^1D)$ indicates the relevant excited state of the oxygen atom in the usual spectroscopic notation; this notation is explained in standard modern texts on spectroscopy.

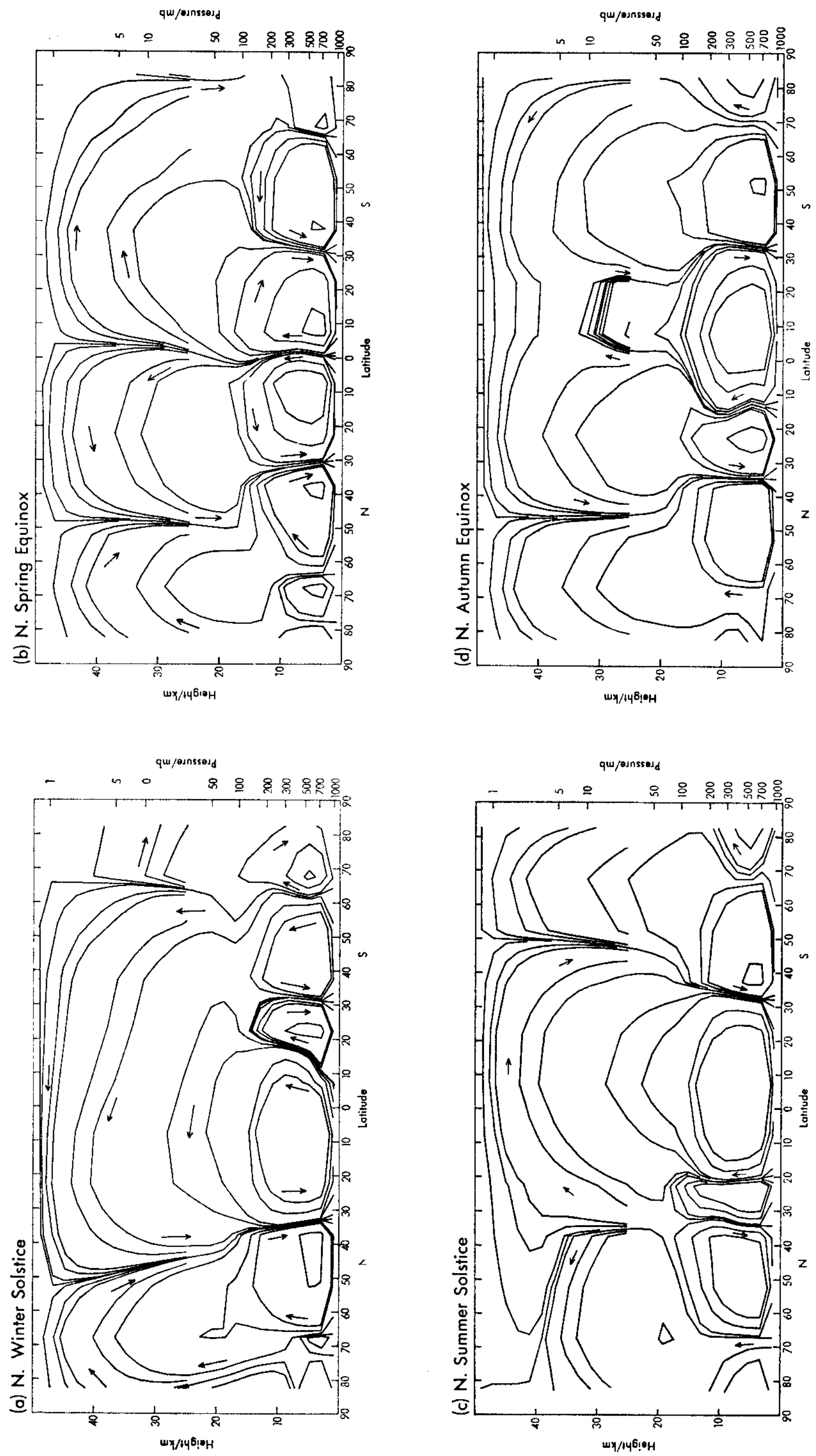

Figure 1. Stream function (arbitrary units) illustrating mean meridional flow for the four seasons.

(a) '*Surface deposition*'. The National Academy of Sciences (1976) gives a summary of various studies (Liss and Slater 1974, Parmalee 1953, DuPont 1971) of the solubility and removal of CFCs by the oceans. They estimate from the limited data available that the mean global removal time for F11 is about 270 years. The considerable uncertainty about the rate of removal by 'surface deposition' is illustrated by the fact that Junge (1976) concludes that the most likely removal time is 800 years. Another possibly important removal mechanism is by dissociation after adsorption on to Saharan dust (Ausloos *et al.* 1977). In view of the general uncertainty about these and other possible loss mechanisms it was decided to represent this by a removal of F11 from the lowest layer of the model at a rate of 1·8 per cent per year at all latitudes. This is a somewhat arbitrary figure, but since in this study experiments were run both with and without this mechanism, it should be possible to adjust the results in the light of future discoveries. There is even greater uncertainty about the removal rate of F12, but since its solubility is estimated to be just under half of that of F11, a removal rate of half that for F11 was taken in this model.

(b) *Dissociation and chemical reactions.* The CFCs are dissociated directly by ultra-violet light in the 200 nm region of the spectrum and are also destroyed by chemical reaction with the excited oxygen atom $O(^1D)$ which is in turn formed during the dissociation of ozone by ultra-violet radiation of wavelengths below 310 nm. Thus for both these processes it was necessary first to calculate photodissociation coefficients, J, in the relevant wavelengths, using the equations

$$J(z) = \sum_l Q(l)\,\sigma(l)\,I(z,l) \qquad (9)$$

$$I(z) = I_0 \exp(-\sum_i \sigma_i \sum_z n_i(z) m(z) \Delta z) \qquad (10)$$

$$m = (1 + z/E)(\cos^2 \alpha + 2z/E)^{-\frac{1}{2}} \qquad (11)$$

$$\cos \alpha = \cos \lambda \cos \delta \cos \theta + \sin \lambda \sin \delta, \qquad (12)$$

where Q is the quantum efficiency
σ is the photon absorption cross-section
I is the photon flux at height z and I_0 is its extraterrestrial value
l is the wavelength
n is number density and i the absorbing species (O_2, O_3)
α is the zenith angle
m is the path length magnification factor
δ is solar declination
θ is local hour angle.

In order to reduce the computation time of the model, ozone profiles were extracted once per month from an early version of the full two-dimensional chemical–kinetic model, although these were modified slightly in the highest levels so that they were in closer agreement with measured values.

The absorption cross-sections for F11 and F12 were taken from Huebner *et al.* (1975) and for O_3 from Ackermann (1971). Mattingly (personal communication) derived the cross-section for O_2 and Tuck and Clough (personal communication) compiled the solar intensities from data of Thekaekara, Broadfoot, Simon and Ackermann. The quantum yields are as in COMESA (1975). The computed photodissociation rate coefficients for latitude 22·5°N for 1 March are shown in Figures 2(a)–(c).

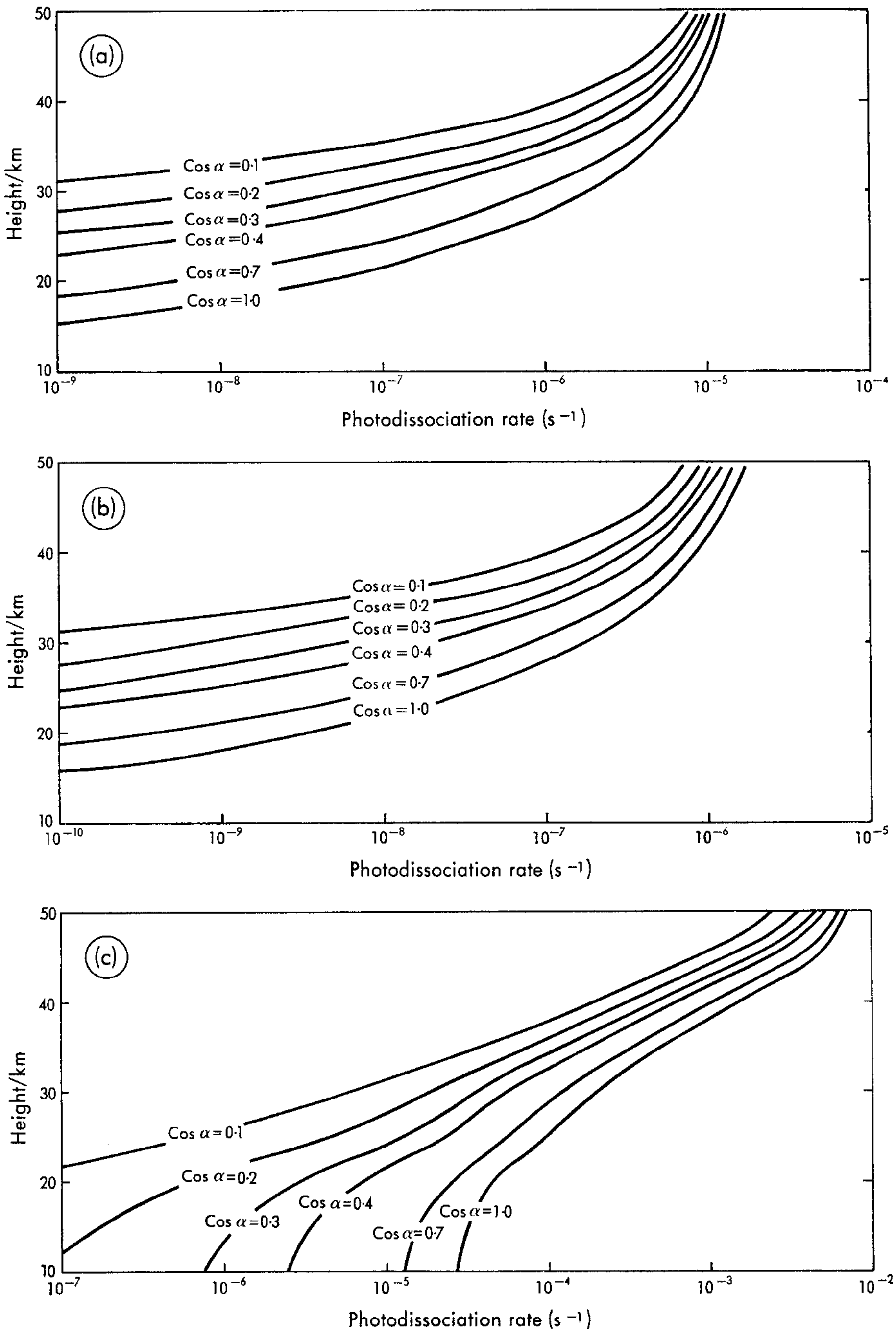

Figure 2. Computed photodissociation rates for 1 March at 22·5°N at stratospheric levels for different solar zenith angles: (a) F11, (b) F12, (c) $O_3 \rightarrow O(^1D)$.

Values of J coefficients were computed for each month, for each latitude, for six values of $\cos\alpha$, for photodissociation of F11 and F12, and also for the dissociation of O_3 to $O(^1D)$. Within the model run linear interpolation was used to obtain values of J for the required time and the value of $\cos\alpha$.

In the calculation of the number densities $[O(^1D)]$ of excited oxygen atoms it was, for simplicity, assumed that the two reactions

$$O_3 + h\nu \rightarrow O_2 + O(^1D) \text{ (wavelengths less than 310 nm)} \qquad (13)$$

$$O(^1D) + M \rightarrow O + M \quad (k = 7{\cdot}0 \times 10^{-11}\ \text{cm}^3\ \text{molecule}^{-1}\ \text{s}^{-1}) \qquad (14)$$

(where M represents some appropriate molecular constituent) were in equilibrium, so that the number density could be obtained using

$$[O(^1D)] = \frac{[O_3] \times J_3}{7{\cdot}0 \times 10^{-11} \times [M]} \qquad (15)$$

where $[M]$ is the number density of air, and J_3 the photodissociation coefficient of O_3 to $O(^1D)$.

The reactions used in this model are

$$CF_2Cl_2 + h\nu \rightarrow \text{products} \qquad (16)$$

$$CFCl_3 + h\nu \rightarrow \text{products} \qquad (17)$$

$$CF_2Cl_2 + O(^1D) \rightarrow \text{products} \quad (k = 5{\cdot}3 \times 10^{-10}\ \text{cm}^3\ \text{molecule}^{-1}\ \text{s}^{-1}) \qquad (18)$$

$$CFCl_3 + O(^1D) \rightarrow \text{products} \quad (k = 5{\cdot}8 \times 10^{-10}\ \text{cm}^3\ \text{molecule}^{-1}\ \text{s}^{-1}). \qquad (19)$$

If J_1 and J_2 are the dissociation coefficients for F11 and F12 then the total coefficients R_1 and R_2 of destruction of F11 and F12 are given by

$$R_1 = J_1 + 5{\cdot}8 \times 10^{-10} \times [O(^1D)]\ \text{s}^{-1} \qquad (20)$$

$$R_2 = J_2 + 5{\cdot}3 \times 10^{-10} \times [O(^1D)]\ \text{s}^{-1}. \qquad (21)$$

The rate for reaction (14) was taken from Husain and co-workers (see Davidson *et al.* (1976)) and those for reactions (18) and (19) from Pitts *et al.* (1974). Davidson *et al.* (1976) indicate that Husain's value is probably too high by a factor of about two, and since Pitts's values were not absolute but relative to that of Husain for reaction (14), all the reaction rates used here for $O(^1D)$ should probably be halved. However, it is to be noted that although this change would double the amount of $O(^1D)$ present in the model (see equation (15)), it would not in fact alter its effect on F11 or F12 in any way, since the two factors cancel out in equations (20) and (21).

Since in this study we are considering non-interactive chemistry, with predetermined ozone profiles, and are not concerned with the products of F11 and F12 destruction, the computation of chemical changes takes on a much simplified form. If n_i is the number density of a species i, and R_i the total rate of destruction, then in these circumstances

$$dn_i/dt = -R_i n_i$$

and hence $n_i = n_{i,0} \exp(-R_i \Delta t)$, where $n_{1,0}$ is the value of n_1 at the beginning of the chemical time-step Δt, which was taken as 10 minutes. Thus, if n_1 and n_2 are the number densities of F11 and F12 at the end of this time-step

$$n_1 = n_{1,0} \exp(-\Delta t \times R_1)$$

$$n_2 = n_{2,0} \exp(-\Delta t \times R_2).$$

It will be noted that a major weakness of the above approach is that the changes in ozone resulting from the effects of the chemistry involving CFCs are not specifically considered. In order to investigate this aspect an additional model run was carried out with reduced ozone amounts (see condition (c) in section 5).

5. The experiments

The experimental program covered the model-years 1931–98 and is summarized in Table II.

Table II. *Experimental details*

Experiment	1(a)	2(a)	3(a)	4(a)	5(a)	1(b)	2(b)	3(b)	4(b)	5(b)	2(c)	3(c)	4(c)
Destruction by photodissociation		X	X	X			X	X	X		X	X	X
Destruction by reaction with $O(^1D)$			X	X				X	X			X	X
'Surface deposition'				X	X				X	X			X
With injections before end of 1978	X	X	X	X	X	X	X	X	X	X	X	X	X
With injections after end of 1978	X	X	X	X	X								
With reduced ozone after end of 1988											X	X	X

The integrations were repeated for both F11 and F12 for a number of different conditions

(1) with no destruction mechanisms

(2) with stratospheric dissociation by solar ultra-violet radiation

$$CF_2Cl_2 + h\nu \rightarrow \text{products}$$
$$CFCl_3 + h\nu \rightarrow \text{products}$$

(3) with (2) and loss reactions by $O(^1D)$

$$O_3 + h\nu \rightarrow O_2 + O(^1D)$$
$$O(^1D) + M \rightarrow O + M$$
$$CF_2Cl_2 + O(^1D) \rightarrow \text{products}$$
$$CFCl_3 + O(^1D) \rightarrow \text{products}$$

(4) with (3) and an assumed rate of 'surface deposition'

(5) with (1) and an assumed rate of 'surface deposition'

The experiments were repeated with the following varying release conditions:

(a) to the end of 1998 with CFC releases at 1975 rates for 1976–98;

(b) to the end of 1998 with no further releases after the end of 1978;

(c) as (b) but assuming that in the years 1989–98 stratospheric ozone amounts were reduced as shown in Table III which is based on data given in Figure 8.6 (without $ClONO_2$) on pp. 8–25 of the National Academy of Sciences (1976) report.

Table III. *Percentage reduction in ozone for years* 1989 *to* 1998

Level (km)	Percentage ozone reduction	Level (km)	Percentage ozone reduction
48	25	27	29
46	37	25	28
43	47	23	24
41	53	21	15
39	51	19	11
37	46	17	11
35	40	15	11
33	35	13	11
31	31	11	9
29	30	9	5

6. The results

To provide a general assessment of the model a comparison is shown in Figure 3 of a model-produced latitude–height cross-section of F11 volume mixing ratio for 1 November 1974 obtained in Experiment 4(a) with observed values for mid-October 1974 given by Krey and Lagomarsino (1975). Model values appear to be rather too high in Arctic latitudes but the general agreement is considered satisfactory.

An illustration of the manner in which solar radiation and transport mechanisms affect the stratospheric distributions throughout the year is given in Figures 4(a)–(d) which show the F12 distributions simulated in Experiment 3(a) for the four seasons of 1978. In the upper stratosphere the values are lowest in autumn at high latitudes owing to dissociation during continuous sunlight with the minimum transferring with season between the hemispheres. In the lower stratosphere the principal feature is the maximum at low latitudes apparently associated with the upward branch of the Hadley cell. The mean motions at higher latitudes do not appear to have a major effect on the stratospheric patterns.

The above diagrams, however, do not illustrate the detailed role of the motions in determining the final distributions of the constituents. In order to study this more closely calculations were made of the fields of the horizontal and vertical fluxes together with their convergences. Typical results for the four seasons are illustrated in Figure 5 for Experiment 4(b) for F12 in the model year 1992 (that is to say, after the termination of injections).

It may be seen that during the northern hemisphere spring the main transfer by the atmospheric circulation of the CFCs into the stratosphere is upwards through the equatorial tropopause. Polewards transport then takes place in the stratosphere in both hemispheres with descent in middle latitudes. There is also a predominance of flux from northern hemisphere to southern hemisphere in the troposphere. The effect of these transports is to produce divergence in the upper tropical troposphere and convergence in the low-latitude stratosphere but also divergence in the southern mid-latitude stratosphere. Thus although the motions apparently made the CFCs available for photochemical destruction (convergence) over most of the stratosphere there are regions where they in fact remove (divergence) the CFCs from the stratosphere.

At the summer solstice in the northern hemisphere the main region of upward flux through the tropopause is in low latitudes and transfer to the southern hemisphere now takes place across the equator at stratospheric as well as upper tropospheric levels. There is a major region of downward flux through the tropopause in southern mid-latitudes. The general effect is to produce flux divergence in the lower stratosphere in the southern hemisphere which is roughly a mirror image of the convergence caused by the ascent in the northern hemisphere. However, convergence occurs at the highest levels at all latitudes (and in all seasons), presumably feeding the photochemical sink. In the troposphere there is also a 'mirror-image' effect with the main convergence to the south of the equator in upper levels, and to the north nearer the surface.

By the northern autumnal equinox the area of main upward flux has returned to equatorial latitudes and the flux patterns are broadly similar to those of the northern spring. The convergence patterns, however, are considerably more asymmetrical, particularly in the stratosphere. Here there is general

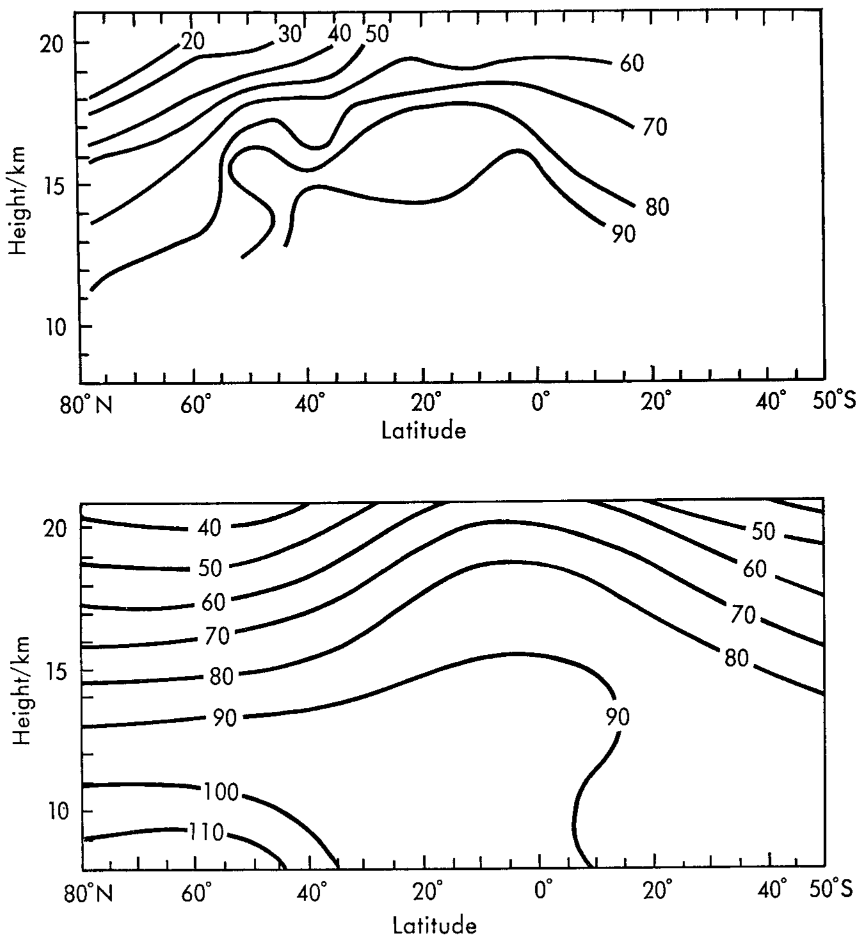

Figure 3. Comparison of latitude–height cross-sections of F11 volume mixing ratio. Upper diagram shows observed values for mid-October 1974, after Krey and Lagomarsino (1975). Lower diagram shows model values for 1 November 1974. For units see caption to Figure 4.

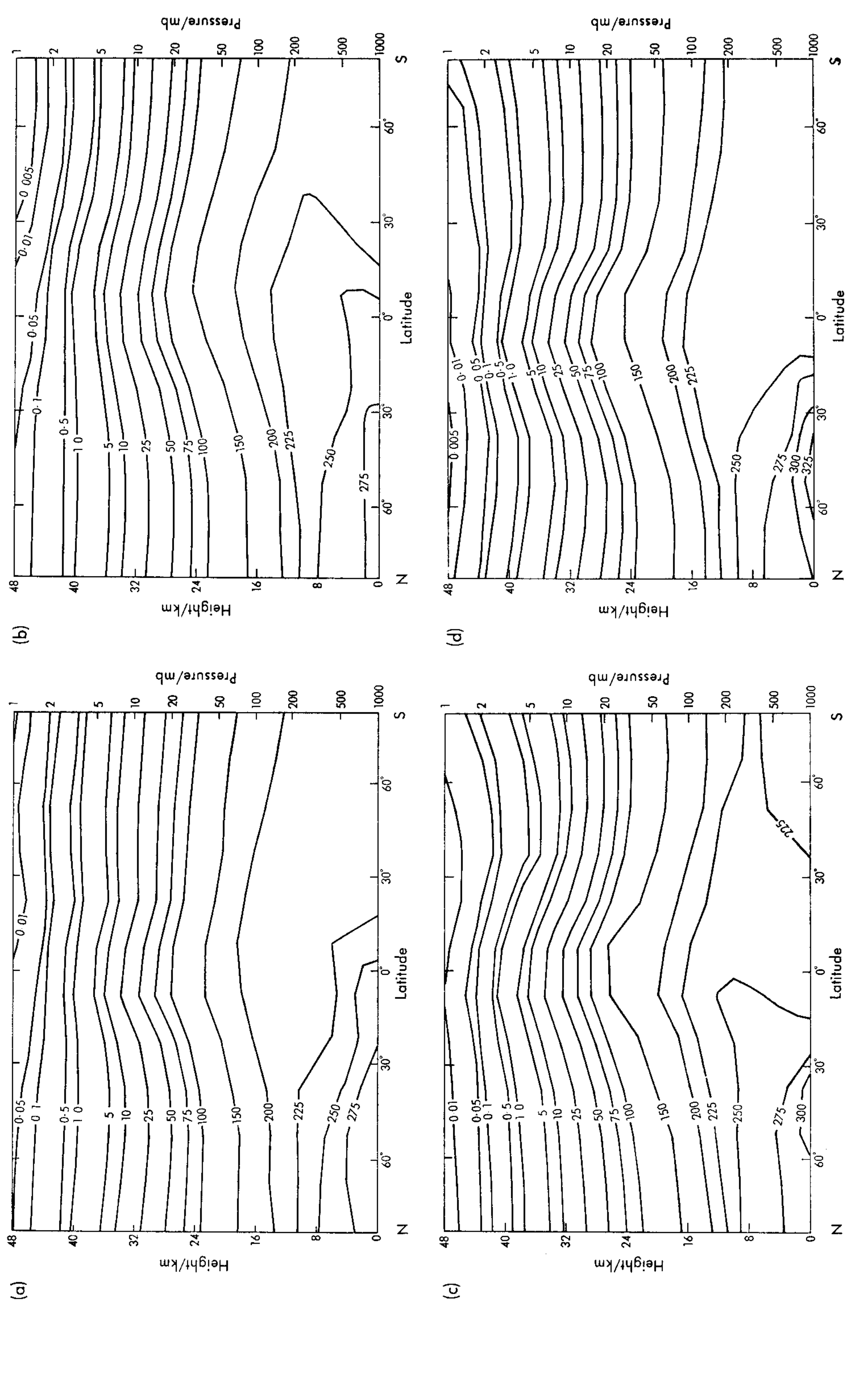

Figure 4. Latitude–height cross-sections of F12 volume mixing ratio (ppt) computed in Experiment 3(a). (a) January 1978, (b) April 1978, (c) July 1978, (d) October 1978. [ppt = parts per American trillion (10^{12}).]

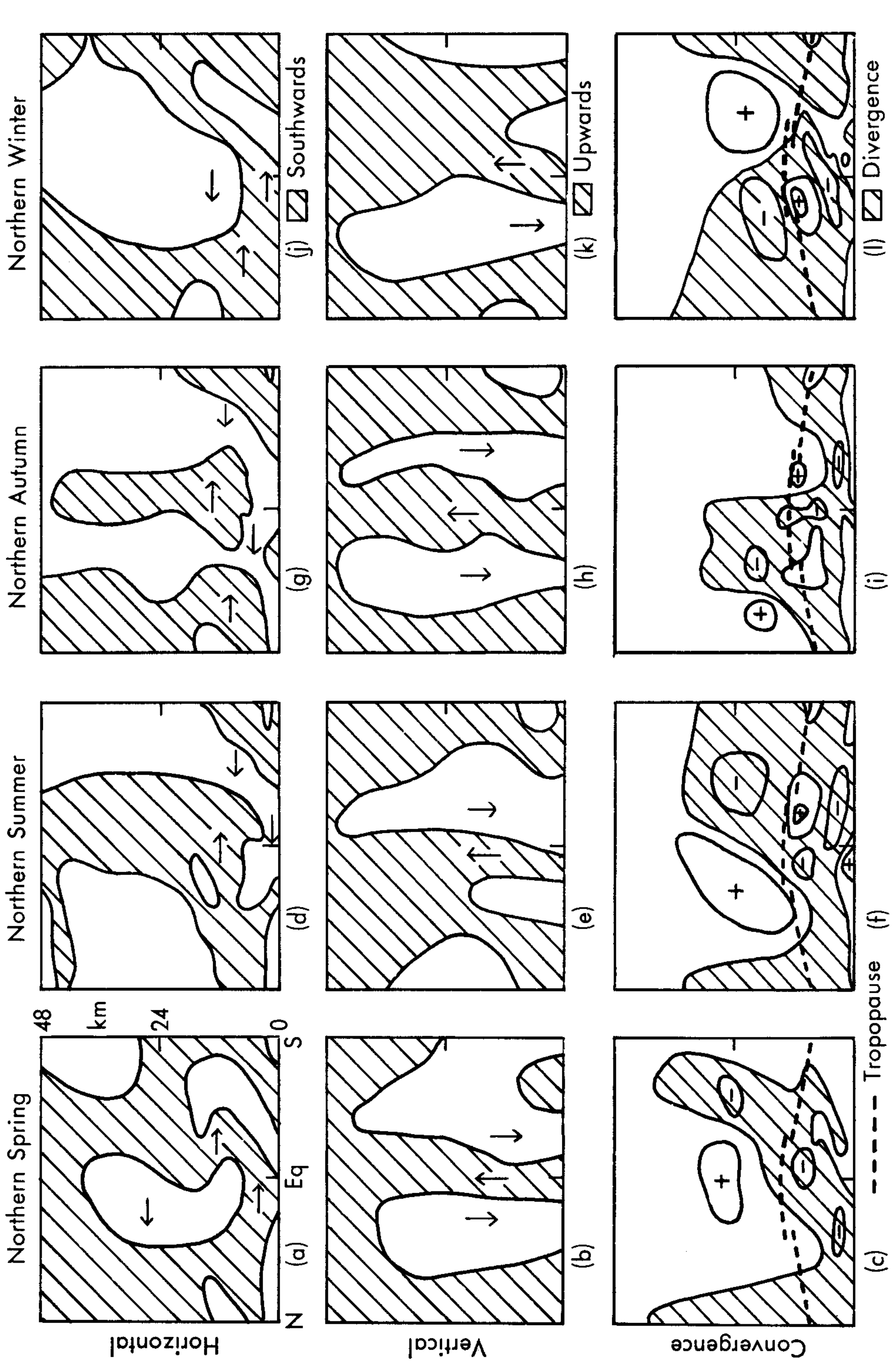

Figure 5. Flux patterns for F12 for Experiment 4(b) for the year 1992.

convergence everywhere except in the tropical and northern middle latitudes of the lower stratosphere. The motions in the latter regions do not act as a supply for the photochemical sink at this time of year.

Finally at the northern winter solstice there is rather general upward motion through the tropopause in the southern hemisphere and large downward fluxes occur in the lower and middle latitudes of the northern hemisphere. Transfers in the stratosphere are generally from the southern to the northern hemisphere. The main flux convergence takes place in the southern hemisphere lower stratosphere at middle latitudes with divergence in most of the lower stratosphere of the northern hemisphere. In the troposphere there is mainly divergence but regions of convergence occur in the upper troposphere at northern mid-latitudes, and in mid-latitudes of the southern hemisphere.

In the main, the flux transfers appear to be dominated by the mean meridional cells, especially the Hadley cell at low latitudes. The convergence–divergence patterns, however, are more complex and in particular there is divergence in the winter hemisphere in the lower stratosphere.

Variations of F11 global averages with time at different levels of the atmosphere are shown in Figure 6(a) for the years 1967 to 1978, in Figure 6(b) for 1979 to 1990 with continued injections, in Figure 6(c) for 1979 to 1990 assuming that injections have terminated in 1978, and in Figure 6(d) for 1989 to 1998 with no injections and lower ozone amounts. Figures 6(a) and 6(b) show that as the injections continue the volume mixing ratio increases at all levels as would be expected. However, the rate of long-term increase at the highest levels is very slow, with the photodissociation almost keeping pace with the upward transport from lower levels. The rate of increase in the troposphere is comparatively rapid and takes place unevenly as the mean circulation patterns change with the seasons. When the injections are discontinued (Figure 6(c)) the increase in the lower stratosphere continues for a few years and is then followed by a slow decrease. If the ozone amounts are reduced, increased penetration of the solar beam and consequently increased destruction of F11 and F12 by photodissociation at lower stratospheric levels will take place. This effect is illustrated in Figure 6(d) where the rates of decrease are appreciably larger than those shown in Figure 6(c).

The F11 mixing ratios in the two hemispheres are shown separately in Figures 7(a) and 7(b). The phase changes between the hemispheres with solar zenith angle and seasonal variations of transport are well illustrated and vary from level to level. Considering first the higher stratospheric levels, both hemispheres show a well-marked seasonal variation with a minimum in the summer due to the change of solar angle. However, the two hemispheres are not exactly in antiphase and this leads to a marked annual cycle in the global values (Figure 6(b)). In the northern hemisphere, where the penetration appears to be greater, the minimum lasts from summer into early autumn, and in the southern hemisphere it extends into late autumn. In the lower stratosphere the hemispheric variations are out of phase with those of higher levels and this must be due to the effects of transport, as illustrated by the convergence zones in Figure 5(f) and (l). There is little annual variation in global amounts in this region. At tropospheric levels there is a marked difference between the two hemispheres and Figure 7(b) suggests that southward cross-equatorial flux is strong in the upper troposphere. The nature of interhemispheric transport, which is expected to be mainly by the mean motions, can be inferred from Figures 1(a)–(d), which suggest that the injected chemicals are carried to the upper troposphere in the upward branch of the Hadley cell and then spread southwards at these levels. This is largely confirmed by fluxes shown in Figure 5 and by the tropospheric configuration in Figure 4. In the experiment in which injections were discontinued at the end of 1978 (Experiment 3(b)), it was found that southern hemisphere totals (Figure 8) continued to increase for over a year after the cessation of injections as interhemispheric transport continued. Surprisingly, after this time the southern hemisphere burden was on average slightly greater than that of the northern hemisphere.

It should be noted that there is a net seasonal movement across the equator of just over 1 per cent of the atmospheric burden.

Finally, Figures 9(a)–(d) show the best estimates currently available from this work of likely F11 and F12 distributions near the end of the century, Figures 9(a) and 9(b) on the assumption that injections continue at 1975 rates and Figures 9(c) and 9(d) on the assumption that they have stopped at the end of 1978.

Turco and Whitten (1975) give F12 mixing ratios in the lower stratosphere for different CFC production histories and tropospheric lifetimes and it is noted that their experiments I_∞ and III_∞ give similar values for 1998 to those shown in Figures 9(b) and 9(d) respectively. Values in Figures 9(a) and 9(b) are about half those given by Derwent and Eggleton (1978) for 'a date in the future when considerable CFC release has occurred' and about one-quarter of the stationary state values given by Rowland and Molina (1975).

7. Conclusions

These studies have provided a means of estimating effects of the various mechanisms on the total residence times of F11 and F12 in the atmosphere and these are summarized in Table IV. These estimates were calculated from global totals one year apart and the separate implied contributions found assuming that the removal rates (reciprocal residence times) are additive.

Table IV. *Calculated residence times*

Destruction mechanism	Using original O_3 values		Using reduced O_3 values	
	F11	F12	F11	F12
	years		*years*	
Photodissociation only	82	193	60	151
Photodissociation and O(^{1}D) reaction	81	182	59	143
Photodissociation, O(^{1}D) reaction and 'surface deposition'	65	143	50	118
Separate implied contributions				
'Surface deposition' only	332	675	329	672
O(^{1}D) reaction only	>6000	>3000	>5000	>2000

The National Academy of Sciences (1976) report concludes that the residence time for F11 is about 50 years and for F12 about 100 years and this is in agreement with the values found in this study when photodissociation, O(^{1}D) reaction and 'surface deposition' are taken into account and reduced ozone values are used. The removal rate due to the O(^{1}D) reaction is about 1 per cent of that due to photodissociation for F11 and 10 per cent for F12. These figures are in agreement with those of Rowland and Molina (1975). The 'feedback' effects of the decrease of ozone amounts due to the destruction by the chlorine species are, however, considerable, and of the same order as the effects of 'surface deposition'.

In addition to its broad confirmation of the numerical results of the one-dimensional models this two-dimensional study has provided additional information on the role of transport, and in particular it has illustrated the importance of cross-equatorial transfer by the Hadley cell. This appears to be a more important factor in the CFC problem than with supersonic aircraft effluents because in the latter case the injections were in the lower stratosphere on the poleward side of the jet, where mean motions are downwards in winter. In addition this study has indicated that the effect of the motions

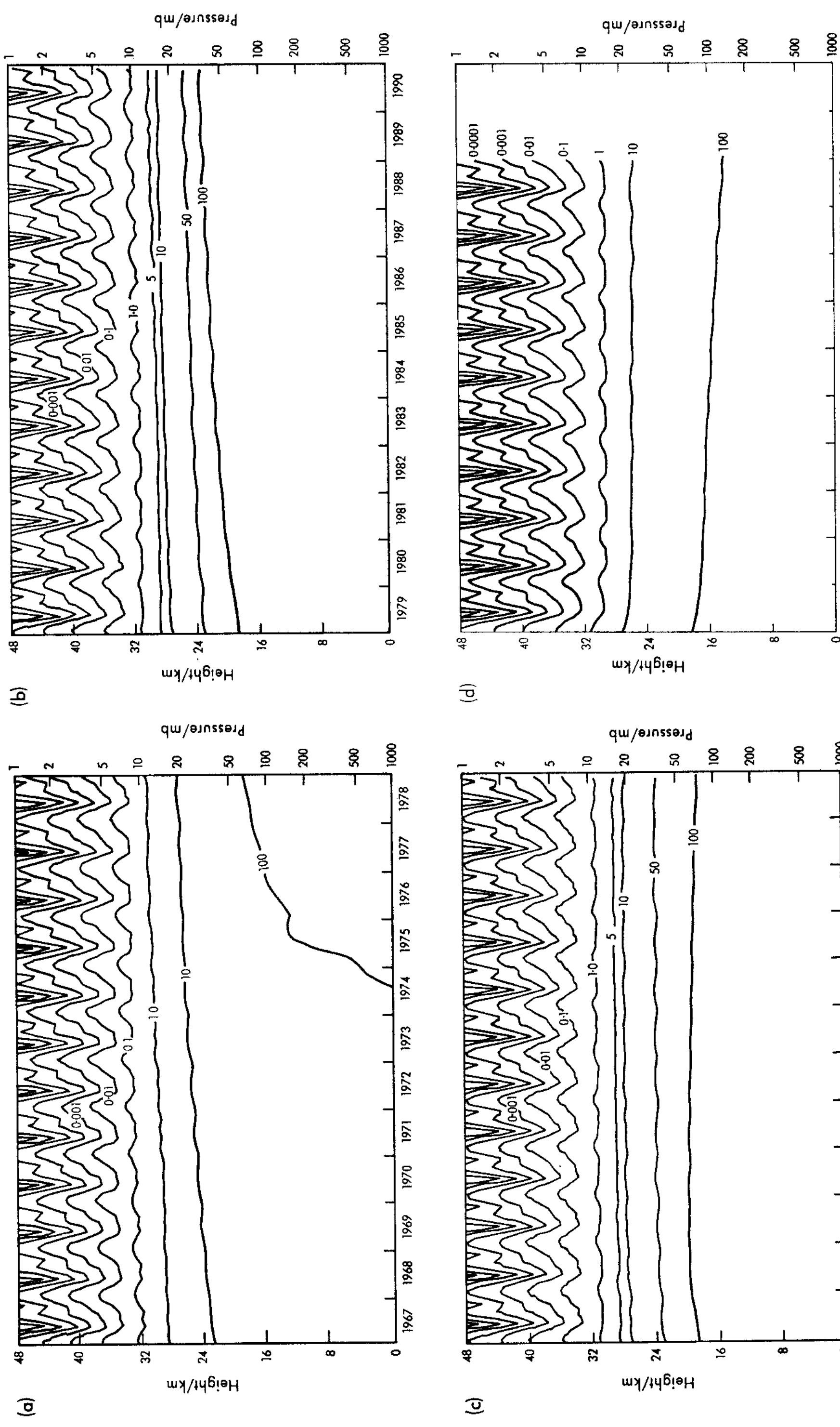

Figure 6. Computed height–time cross-sections of globally averaged F11 volume mixing ratio (ppt). (a) January 1967 to December 1978, Experiment 4(a). (b) January 1979 to December 1990, Experiment 4(a). (c) January 1979 to December 1990, Experiment 4(b). (d) January 1989 to December 1998, Experiment 4(c).

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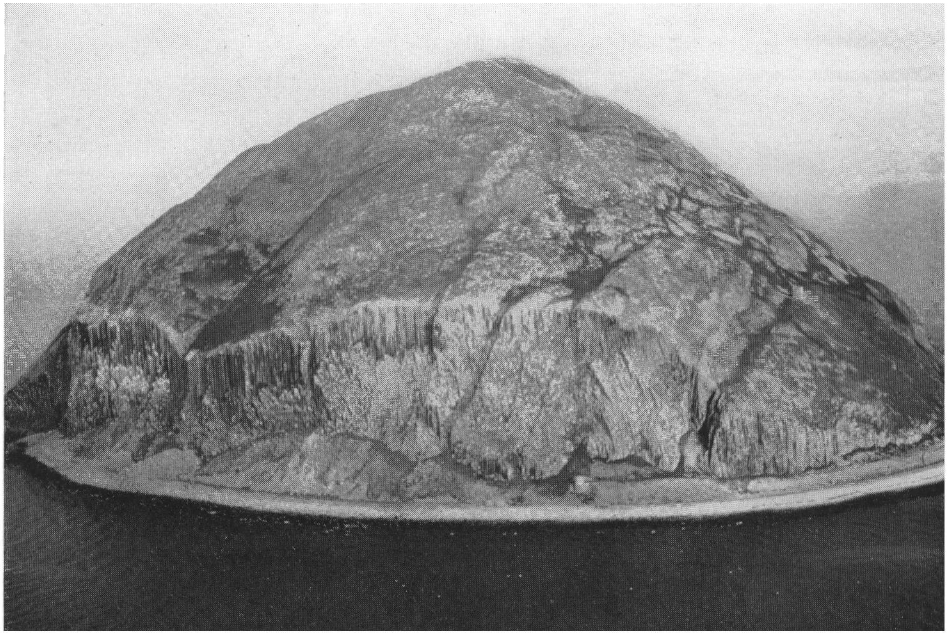

Plate I. Ailsa Craig viewed from the south (see page 250).

Plate II. Ailsa Craig viewed from the east.

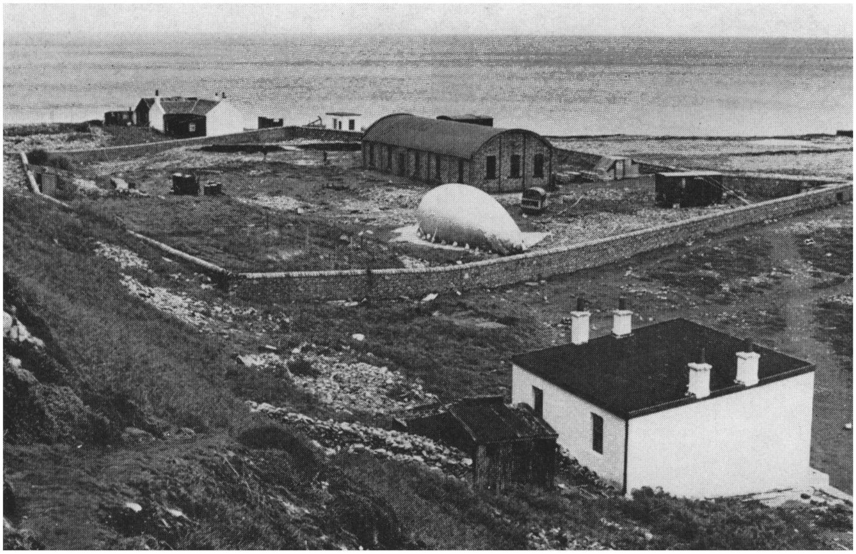

Plate III. RAE balloon lying in the grounds of the old gasworks on Ailsa Craig.

Plate IV. Northern Lighthouse Board buildings and light on Ailsa Craig. The RAE balloon is visible at the bottom left-hand corner.

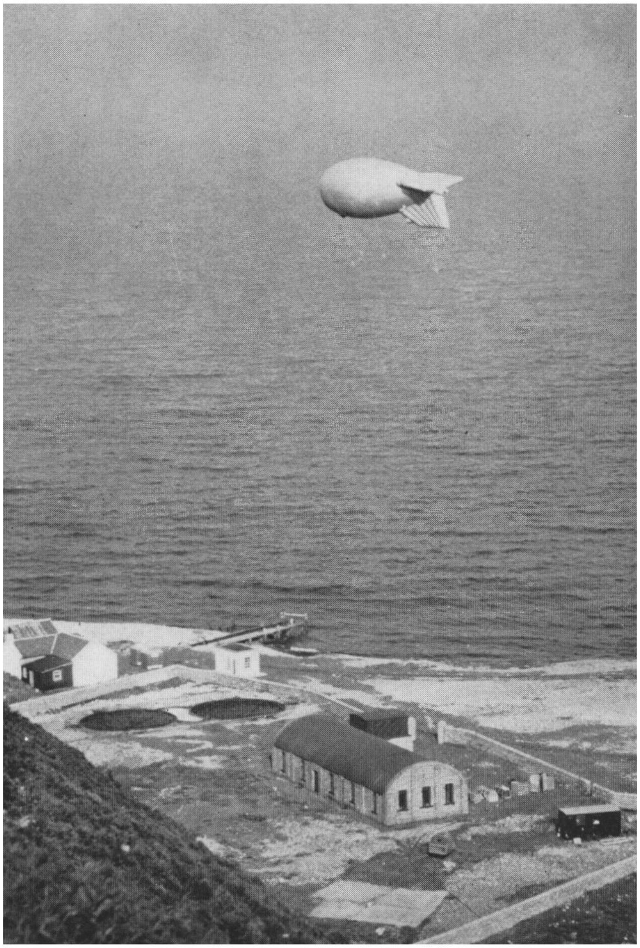

Plate V. RAE balloon flying over the old gasworks on Ailsa Craig.

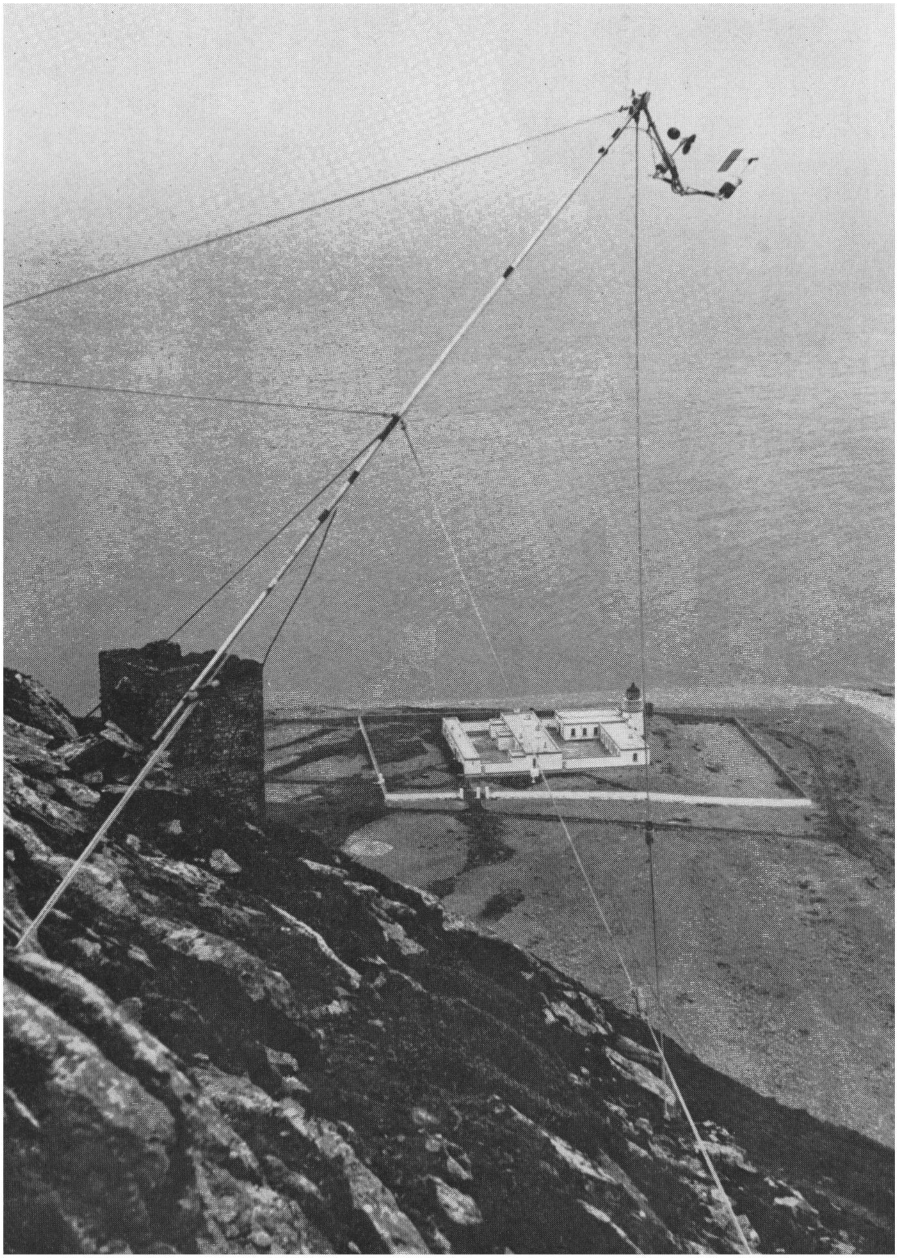

Plate VI. Vector-averaging wind recorder mounted on the hillside overlooking the lighthouse on Ailsa Craig. The ruins of the old castle are visible.

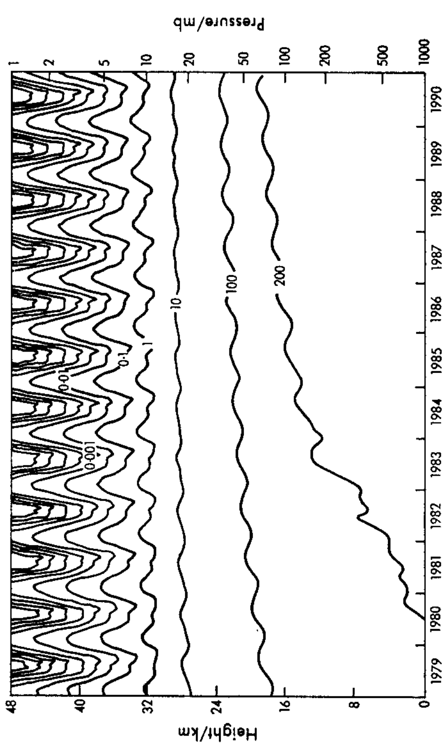

Figure 7(a). Values of F11 volume mixing ratio (ppt) for the northern hemisphere corresponding to the global total of Figure 6(b).

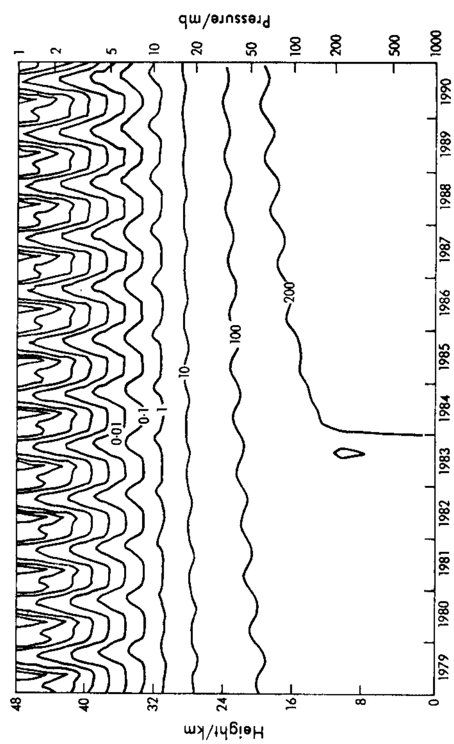

Figure 7(b). Values of F11 volume mixing ratio (ppt) for the southern hemisphere corresponding to the global totals of Figure 6(b).

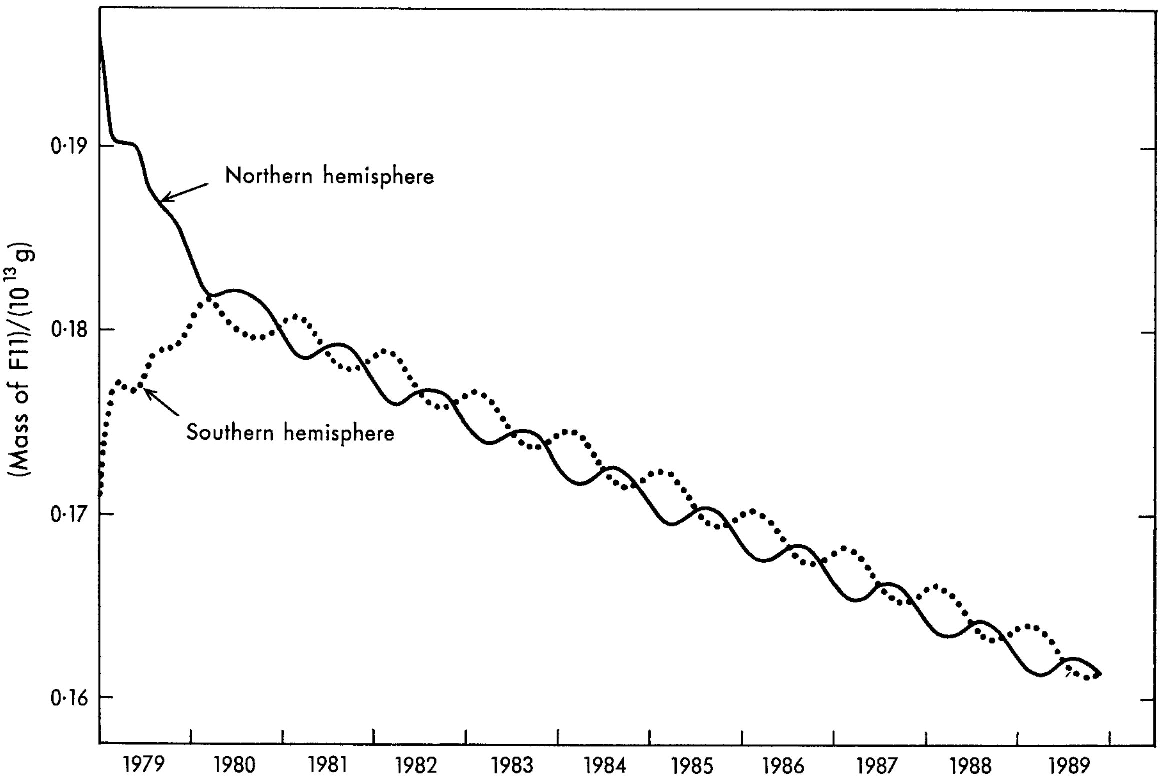

Figure 8. Hemispheric total masses of F11 during the period January 1979 to December 1989 obtained in Experiment 3(b).

is to remove CFCs from the stratosphere in some periods and locations (for example mid-stratosphere in winter—see Figure 5) as well as generally providing the means whereby CFCs are transferred from the source regions in the lower atmosphere to the sink regions in the upper stratosphere, thus illustrating the complications of the total dynamical–chemical problem.

Acknowledgement

The author wishes to thank Dr R. J. Murgatroyd and Dr S. A. Clough for their very considerable advice and help.

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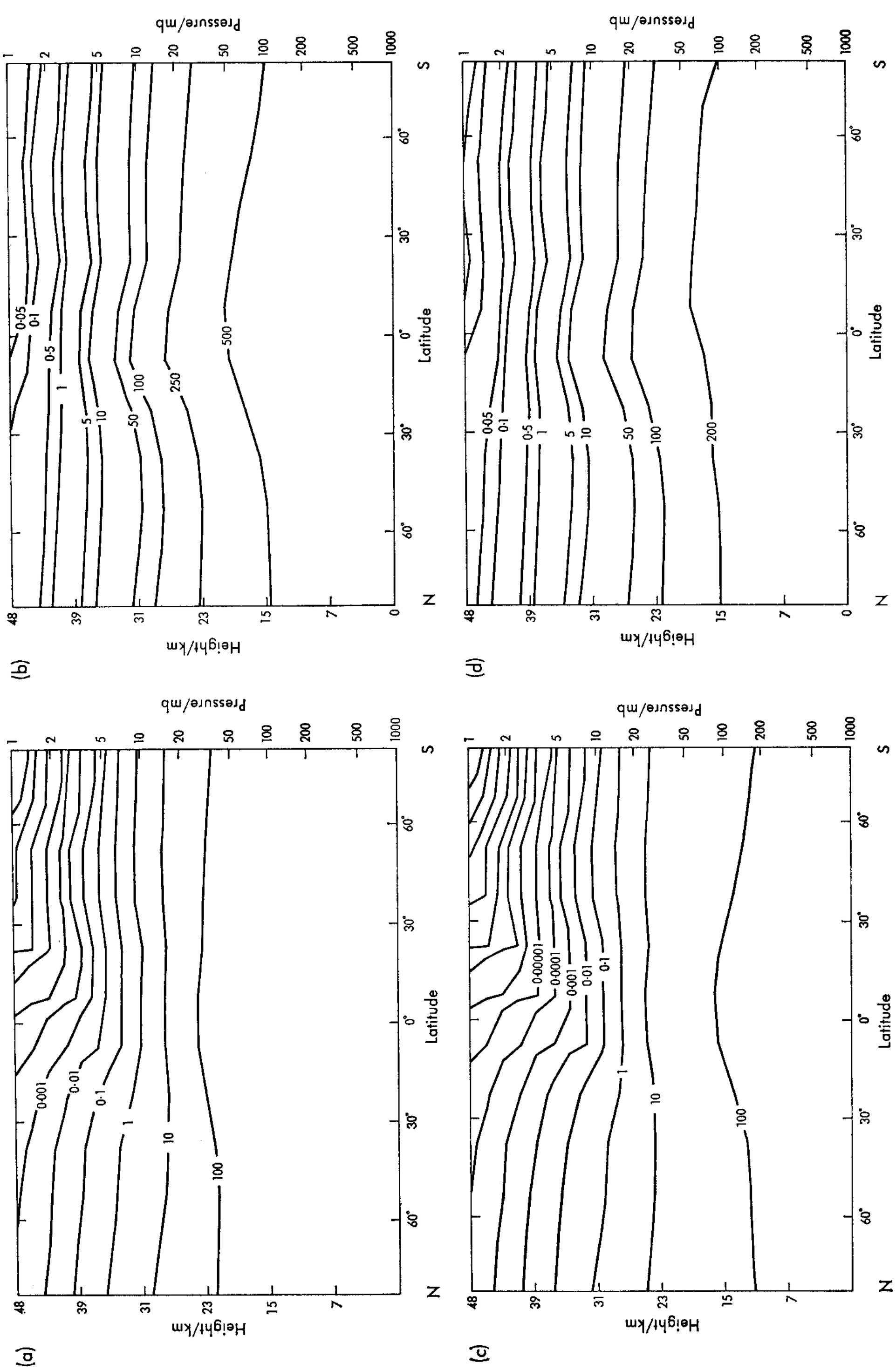

Figure 9. Predicted cross-sections of volume mixing ratio (ppt) at the end of 1998. (a) F11, Experiment 4(a). (b) F12, Experiment 4(a). (c) F11, Experiment 4(c). (d) F12, Experiment 4(c).

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Memoirs of an Army Meteorologist

By H. Cotton, M.B.E., D.Sc.

Part 1

We print this month the first of a series of extracts from the unpublished memoirs of Dr H. Cotton who, until his retirement in 1954, was Professor of Electrical Engineering at Nottingham University. He has sent us a copy of his memoirs—which contain many details of his childhood, early education, and personal reminiscences as well as his account of his experiences in 'Meteor'—and has kindly granted us permission to make extracts from them for publication in the *Meteorological Magazine*.

Dr Cotton spent his childhood in Hanley in the Potteries, and won scholarships to Manchester University where he studied under Rutherford. As a boy he became a skilled amateur player of the cello.

The Meteorological Section of the Royal Engineers, or 'Meteor' as it was generally known, was commanded by Captain (later Lt.-Col.) E. Gold, F.R.S., who described its work in the special issue of the *Meteorological Magazine* celebrating the centenary of the Office.* Except for that of Col. Gold himself, all names used by Dr Cotton are fictitious.

At the commencement of my final year at the university I tried to join the O.T.C.; only tried, because besides being left-handed, I was almost completely left-sided. I was therefore very clumsy at rifle drill but was a fairly good shot provided that I could hold the butt at the left shoulder and manipulate the breach bolt with the left hand. This of course would not do; if I was to shoot an enemy it must be right-handed or not at all. But for this I might have been one of the sixty thousand casualties of the first day of the Battle of the Somme, for the regiment I would have joined, the Fifth North Staffs., was almost completely wiped out. It is curious to realize that, if I had been right-handed, these memoirs might not have been written, or, if they had been written, would have been entirely different.

At the time of the outbreak of war in 1914 I was a lecturer at the Technical College, St Helens, Lancashire. I was responsible for the whole of the instruction in Electrical Engineering, in Advanced Machine Drawing and Design, and in Advanced Practical Mathematics. I had classes every week-night from seven to ten, every Saturday afternoon from two to five, and part-time day classes on two days a week. It was a formidable program which could not have been sustained if the evening and Saturday classes had been continued beyond Easter. Fortunately, after Easter, there was, apart from day classes, only light administrative work; without this rest I doubt if I, or anyone else, could have continued.

[Soon after the outbreak of war, Dr Cotton attempted to join the motor-cycle machine-gun corps, but the Education Authorities would not release him.]

On September 25th of that year, 1915, the British launched their first major offensive of the war. It was named the Battle of Loos after the town of that name situated in the middle of a vast mining complex. Characteristic of this industry, the terrain was broken land, littered by ramshackle buildings of all kinds, crossed by roads and lanes and railway lines, hopeless for attack but ideal for defence

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* Gold, E.; The Meteorological Office and the first world war. *Meteorol Mag*, **84**, 1955, 173–178.

since almost every feature could be converted into a strong-point. Perhaps most important of all, the enemy had possession of every one of the spoil heaps, these giving them such perfect observation that they could note every move made by the British, see the position of every gun, see everything in fact.

Apart from the almost lunatic choice of terrain for an offensive battle and the stationing of the reserve twenty miles away so that when they were needed they had to make a long forced march, the special feature of the battle was that the British used gas for the first time. It was supposed to be a profound secret known only to the Higher Command, but the gas was made at Widnes, and many of the soldiers whose homes were in or near Widnes knew from letters from home that 'Roger' was coming out, 'Roger' meaning chlorine. There are always those who are unable to keep a secret and soon everybody knew this supposed secret, the local population knew it, and through local spies the Germans also knew. So from their ideal observation position they watched the gas cylinders being placed in position in a trench and informed their gunners just where the cylinders were.

Now gas released from cylinders is a very treacherous weapon since to be effective the surface wind must be about three or four miles an hour and must be steady in direction as well as in velocity. But light winds are very fickle, liable to sudden changes in direction, and that is what happened. At first it appeared that the gas would be a great success, but suddenly the wind changed direction and the gas was blown back. This is what the Germans were waiting for; their meteorological service, very much superior to ours at the time, had anticipated such a change. Immediately their guns opened fire on the gas cylinders which, when broken, poured out an almost solid cloud of chlorine. The reserves, tired after their forced march, ran straight into it. The battle was described by the press as a great victory because a few yards of useless territory were captured. In fact it was a tragedy of lessons not learned and courage wasted. In his book 'Fifth Army' Gough wrote 'Both Sir John French and Sir Douglas Haig made energetic protests against launching this attack at Loos . . . the fighting was for "the cause", *a stern necessity which weighed more heavily on us every year as the war continued*' (my italics).

To all intents and purposes the sacrifices in men and material had been in vain, but one important lesson had been learned. It was that the vagaries of purely local winds cannot be forecast from a synoptic chart covering Europe and much of the Atlantic Ocean. It is necessary to have observers covering the whole of the area for which such information is required. So, a few weeks later, I received a letter from the War Office asking if I would volunteer for service in a Meteorological Section R. E. to be stationed in France. This time my request for release by the Education Authorities was granted, and I was to become that *rara avis* a peg in a hole of the right shape and I dropped all ideas about serving with the motor-cycle machine-guns. I immediately wrote an acceptance, and a few days later I received a second communication instructing me to sign on at any convenient Recruiting Station and then await further instructions. I went once more to J.J. [as the Principal was colloquially referred to] and asked if I might have a day off so that I might see my parents; 'you never know' I said. He agreed. 'That will mean someone taking one of your evening classes' he said 'and that someone will have to be me'. He settled for the evening of the Lancashire and Cheshire examination in electrical engineering. I was very doubtful but said nothing beyond thanking him for his help.

I said goodbye to my parents and signed on at the Hanley Recruiting Office as I knew the Recruiting Officer there. I received the King's shilling, which I still have somewhere. When I saw the class the following week I asked what J.J. had taught them and they all laughed. 'Was it very amusing?' I asked. 'It certainly was' said one; 'he said that a line of force was like a string of sausages'. 'Yes' said another 'he worked out a numerical problem and couldn't get the right answer'. 'I think you had better forget all that he told you' I said, and then continued with a proper lesson.

At the very beginning of the New Year of 1916 I received instructions to report at the Queen Mary R.E. Barracks at Chatham. Army barracks are pretty much the same wherever they are and there is little point in describing this one except to say that it was not made for physical comfort. I gave my particulars, name, age, address, religion. That was United Methodist, but if I had said that I had no religion I should have been put down as Church of England. It seemed that I was joining a very religious army. This interrogation over and my pedigree duly recorded I turned away and a sergeant who was standing by said in a sneering voice 'And where have you been all this time my little man?' I wasn't having any, having already sensed the contempt of the old army for us mere civilians. So I said nothing, gave him a weak smile and passed on. The next man was made of sterner stuff and to the same silly question he replied 'Helping my bloody country while you lot were losing the bloody war'. I thought that the sergeant was about to drop dead, and hoped he would. Instead, he recovered himself after visible effort and marched off. 'That was brave of you' I said, 'but I am afraid you will be for it' and I was right. My fatigues were not so bad, peeling spuds one day and acting as housemaid in married quarters on another. The brave man seemed to spend most of his time cleaning latrines and I hoped he would be able to get his own back although I could not imagine how it would be possible. As far as I was concerned the worst bit was the CSM injection which made one feel decidedly miserable for a day, after which it wore off.

I joined a sizable bunch of men about my own age and I heard one of them say that there was a rumour to the effect that they would be going overseas in a day or two.

'Do you all belong to Meteor?' I said.

'Meteor, what's that?'

'It's the unit I have been instructed to join'.

'Never heard of it'.

'What are you then?'

'A gas company, we are the blokes who will turn on the bloody gas taps. Some bloke at the War Office decided that to turn on the taps properly one must have an honours degree in Chemistry, so here we are, a bunch of Chemistry teachers'.

Turning gas taps was not my idea of serving King and Country and I realized that it was time I saw the Commanding Officer and explained the situation. Trying to see the C.O. was almost as difficult as trying to see God, but by working upwards from lance-corporal up the ladder of rank to the adjutant I at last gained permission to see this august personage. I was ushered into the presence, escorted by an enormous sergeant, and explained the position. I handed to him my original letter from the War Office. He was very pleasant and not at all fearsome, not to me anyway, and he started things moving straight away. I was issued with a railway warrant to Newark and instructed to report to the R.E. Barracks there. I travelled by the midnight train from King's Cross and arrived in the early hours.

One thing I brought with me from the barracks at Chatham was a red fibre identity disc stamped H. COTTON, UM, R.E. 160163. The UM stood for United Methodist. I discovered that everyone entering the Army, no matter which service, had to possess an identity disc, and he had to have a religion even if he had never belonged to any religious denomination. If he declared that he had no religion, then, automatically, he became a member of the Church of England. It would appear that the Army authorities could not possibly allow a man to attend a compulsory religious service unless he belonged, if only in an Army record, to some religious denomination. I had already found out that one could not be allowed to handle a rifle left-handed—I happen to be left-handed—but I doubt if there were any troops who, like Cromwell's Ironsides, went into battle on a prayer and a bible. I spent what remained of the night on a sloping board in the guardroom and, after breakfast at the barracks, recited once again all my particulars. I also underwent a medical test once again, a test which at that stage of the war I should have passed even if I needed propping up. Having already had a CSM injection at Chatham, I was spared a repetition, for which I was thankful, as the after-effects were unpleasant.

I was directed to a civilian billet and instructed to report each morning after breakfast, and that was all.

Newark is a very pleasant town, and apart from the necessity to report each morning after breakfast, and before I was provided with Army uniform, I was, to all intents and purposes, a holiday-maker whose expenses were paid by the State. I have always been content with my own company and I went on long walks into the pleasant countryside or along the river banks, watched the express trains at the level crossing on the Lincoln road—I retained my love of railway engines until the sad ending of the steam era—and practised on the violin so that I became quite proficient in my unorthodox manner of playing it. [The violin referred to by Dr Cotton belonged to the owners of his billet, and he played it as though it were a miniature cello.] I also browsed in the town library. Newark, especially in former years, was an extremely important town because it was at a river crossing. I therefore read the history of the town with very great interest.

The day came when I was provided with Army uniform complete with corporal's stripes. For a time I was still free to do what I liked but there was now the irritation of having to salute, which was a nuisance as there were always plenty of commissioned officers about. So I largely avoided the town—I had thoroughly explored it by then—and spent most of my time walking.

Early in 1916 I received information that I was to proceed to France. I was given a railway warrant to King's Cross and told to report to the Railway Transport Officer there, who would give me further instructions. I received no military training whatever, no square bashing, no small arms drill, nothing but the ability to salute, and this I always did badly. Still, I had my corporal's stripes. I presumed that if by any mischance I should meet the enemy I should have to use my initiative. This was my preparation to 'fight the foreign foe'.

The troopship left Southampton in the early hours of the morning. Because I left Newark before breakfast time and there was no chance of a snack at Waterloo even if I could have pushed my way through the crush in the refreshment room I was feeling decidedly peckish. I and all the other troops who were waiting to embark were served with strong sweet tea and two of those army biscuits which look exactly like large dog biscuits. After eating them, whatever they were, I was still feeling hungry. Fortunately the sea was calm, so we were told, for there are few things worse than being seasick on an empty stomach.

We landed at Le Havre and we again were served with tea and dog biscuits. There was one lot of men belonging to Strathcona's Horse, obviously cavalry by their uniform and equipment; I had never heard of the regiment before. Naturally, at that time I knew nothing of the conditions at the fighting fronts but I wondered what use cavalry could be on broken terrain, riddled by shell holes, with a continuous belt of trenches two and three deep, with communication trenches and iron pickets and barbed wire all over the place. The High Command retained their obsession with cavalry far too long. There could be no repetition of Omdurman with such terrain and against an enemy equipped with every conceivable device for killing at a distance.

We stayed at a so-called rest camp near Le Havre and went by train the following morning to Rouen where we stayed another day and night. I managed to get into the town which was of double interest, first its great historical importance and second its beauty. Of course, I visited the spot where Joan of Arc was burned, surely one of the greatest crimes in British history, and I looked up and round at all the buildings in the square so as to see the last things that she would have seen. Then train again, a long slow journey to Abbeville. I had to change there and this gave me a chance to examine a monster of a locomotive with a square funnel, and, by the look of it, all its pipes on the outside. I couldn't imagine a more ugly engine, especially in comparison with the sleek beauty and clean lines of so many British locomotives. It looked a powerful brute. We were all longing for a drink so I borrowed two dixies and took them, along with my own, to the driver, who filled them with boiling water straight from the boiler. Someone in the carriage had candles so that most of the heat lost on the walk back, but not all, was made up and with plenty of tea from the iron rations there was tea for everybody. It was slightly oily but we didn't mind that.

The new train seemed to wander all over the north of France. At every crossing there were hoards of children shouting 'Bully beef, souvenirs', demonstrating the generosity, so often misplaced, of the British Tommy. It was said that many of the peasants had their cottages lined with tins of bully beef, and although this was a gross exaggeration it was a pointer to the extent of this foolish giving away of things which the donor might need for himself later on.

After what seemed an eternity the train arrived at St Omer station, some distance from the town. I had been ordered to report at a place called Helfant and I had to walk. So I asked a man on the platform 'Combien de kilomètres y-a-t-il d'ici à Helfant?', airing my sixth form French. I forget how many kilometres it was, but it was a long walk uphill all the way, and my burden, heavy pack and greatcoat, seemed to become heavier with each step. Helfant is a small village on a high plateau and the first thing I noticed was a cup anemometer rotating merrily. As there were no Meteor personnel there I assumed that there had once been a meteorological observation station, and that it was now abandoned. I heard the sound of gunfire for the first time. There was a mess where I had the first good meal since I left England. My billet was a barn, comfortable enough, as there was plenty of dry hay. I intended to go for a long walk but the plateau was so bare and uninviting, so I thought I might as well go into an estaminet which seemed to be doing a roaring business. I was still hungry. The man in front of me ordered 'doos oofs, pomme de terre fritz, pain et beurre, café avec'. It looked very good so I ordered the same. It was good, in fact it is still, after all these years, a favourite dish of mine. As there was no point in going for a walk I stayed for quite a while talking to anyone who wanted to talk. The war was not even mentioned. When I turned in, the guns were still rumbling but when I awoke they were silent. After breakfast I trudged back to St Omer station, not so tiring this time as it was downhill all the way. I caught a train which also seemed to wander over the whole of northern France. It took me back to Abbeville where I caught another train and reached Hesdin, Second Echelon G.H.Q. in the late afternoon.

I reported immediately to Meteor and after the Sergeant Major had made sure that there were no buttons undone and that my cap was on straight I was ushered into the presence. Colonel Gold had a slightly saturnine appearance which belied his nature although, as was his right, he could be very angry if things went wrong. He questioned me about my university career; was I any good at Mathematics and Physics? He wrote me a differential equation and asked how I would solve it, also a number of questions about certain aspects of Physics, particularly those pertaining to the science of Meteorology. He seemed quite satisfied and after a while I was dismissed and told to report again to the S.M. who would give me further instructions. These were to find my billet, which was in the infantry barracks, leave my kit there and be back in time for dinner. The prospect of dinner was cheering but the billet was the reverse.

The barracks were a plain stone building, uglier I think than any building I had ever seen before. It was old at the time of the 1870 war with Germany. The rooms were large enough to take, I should say, twenty men. Instead of a door there was a wide open archway, and directly opposite, high up in the wall, a window, small for the size of the room. The floor was of stone and there was nothing to give protection against its cold hardness; no straw, no blankets, nothing. I wondered what kind of a night I was going to have. I found a tap, cold water of course, one could not expect even the simplest of luxuries in such a place, and was thus able to wash off the grime of the long hot railway journey. I had this bare room to myself; in fact, vast as the building was there seemed to be very few people in it. As I anticipated I had a very uncomfortable night, not having had time to become accustomed to the absence of luxuries. I was very thankful when morning came, after what seemed an interminable night. I washed and shaved at the cold tap and made my way back to Meteor.

The organization of Meteor was as follows:

(1). *The headquarters staff*. The O.C., the adjutant and a junior officer, all professional meteorologists in civil life. A staff of clerks from S.M. to corporal; there was no rank below corporal in the whole of Meteor, apart from officers' batmen who were privates seconded from infantry regiments.

The work consisted of the collection of data from as much of the world as possible so that the synoptic charts could be drawn. All over the world, in enemy territory as well, observations were made at what were called the fundamental hours, namely in GMT 7 a.m., 1 p.m., 6 p.m. and 1 a.m. The data were sent by priority telegram so that the chart could be drawn up as soon as possible and consisted of barometric pressure corrected to mean sea level; barometric tendency, i.e. whether up or down and the rate of change; wind direction and force; temperature; precipitation, i.e. rain, hail or snow; thunder if any.

From the 7 a.m. chart the O.C. drew up the forecast for the next twenty-four hours and this was supplied to the Commander in Chief whose headquarters were at Montreuil, First Echelon G.H.Q. Later on Meteor moved to Montreuil so as to be immediately available to the C in C when required. Data were also received from all Meteor observation stations in France, also by priority telegram. Thus the current weather conditions for the whole of the fighting area were known at Meteor headquarters.

(2). *Army Headquarters*. The staff consisted of a Meteorological Officer and two observers, both corporals. Data for the construction of the 7 a.m. chart were received by priority telegram and the chart when completed was taken by the officer to the General of that particular army. The weather and its probable tendencies were discussed. The two observers made local observations of all the phenomena required for the synoptic chart, also wet- and dry-bulb thermometer readings, from which the humidity could be calculated, the amount of rain and the amount of sunshine on the previous day. Also the kinds of cloud and their amounts and an estimation of their directions, velocities and heights. A vitally important observation was that of wind velocity and direction in the upper air to as great a height as possible.

For this purpose small balloons were filled with hydrogen so that they could just lift a certain weight; when freed from this weight and when released they rose at a rate of five hundred feet per minute. Actually, this only applied if there were no vertical air currents. The balloon was followed by means of a special theodolite whose telescope tube had a right-angled bend so that, no matter what the position of the balloon, the eyepiece half was always horizontal. Observations of azimuth and elevation were made after one minute, the balloon then having ascended vertically 500 feet; after another minute at 1000 feet and then after two-minute intervals at 2000, 3000 feet and so on for as long as the balloon could be kept in sight. Occasionally, on a clear day with little wind, observations were made up to 20 000 feet.

These observations were made at the fundamental hours including 1 a.m. For this purpose it was necessary for the balloon to carry a suspended light and many experiments were made to find the most suitable. A flare, a large version of children's fireworks, was the most convenient but it was not only heavy, but as it burned away its weight was progressively reduced thus affecting the rate of vertical climb. The final solution was a Chinese lantern made from tracing paper and carrying a toy candle. It was ironical that a toy which could give delight to children was used to facilitate the slaughter of fellow human beings. The possibility of error due to vertical components of the total wind had to be accepted since, to avoid this error, it was necessary to have two theodolites situated a long way apart following the balloon. Under war conditions this was not possible (a) because of the inconvenience and the necessity for two more observers, and also (b) because the complex computations would have taken too long.

The chief function of these pilot-balloon ascents was the determination of wind corrections for the artillery, for times of flight ranging from those of field guns with ranges of a few thousand yards, up to the heaviest guns with ranges up to ten miles or more.

These corrections were deduced as follows: for each time of flight the trajectory was known, this being a departure from the parabola of elementary mechanics because of air resistance. Also the height of climb was known and this was divided into horizontal zones, the time spent in each zone being calculated. Also the mean wind velocity and direction for each zone was known from the results of the pilot-balloon ascent. For each zone the mean wind velocity was weighted by the time spent in the zone. All these weighted velocities were treated like forces and the mean obtained by giving each its appropriate velocity. Actually the calculation was reduced, for practical purposes, to a series of factors so that the wind corrections for half a dozen times of flight could be calculated in a few minutes, reduced to a code, and sent by priority telegram to the battery commands.

(3). *Two-observer posts.* As the name indicates there were two observers and they were attached to an important command such as a Divisional Headquarters. The observations made were the same as those at Army Headquarters except that there were no pilot-balloon ascents. Observations were made at the fundamental hours and at the intermediate times of 4 a.m., 10 a.m., 4 p.m. and 9 p.m.

(4). *Single-observer posts.* These were distributed along the whole of the battle area and as close to the front as possible, the site for the observations post being obviously chosen in accordance with its meteorological suitability. Observations were made only of wind velocity and direction, the instrument used being a delicate portable anemometer. Priority telegrams were sent to G.H.Q. and Army H.Q. at the four fundamental hours, these including the data for the preceding intermediate observations. The observer also compiled a weather diary giving day-to-day information such as wind, weather in general, cloud amounts and kinds.

The most important duty of these observers was the sending of gas alerts if the wind approached within two points of the danger direction for his particular sector of the line, and gas warnings if it moved to only one point. The telegrams giving this information were sent to Corps and Divisions as well as G.H.Q. and Army H.Q. They were first priority which meant that the signaller had to deal with them immediately even to the putting off of other telegrams no matter who the sender might be. Thus when the wind was in a dangerous quarter it was essential that the observer must be vigilant in the lookout for changes towards the dangerous direction. These changes could be very sudden and could not therefore be forecast from the synoptic chart.

From the personal point of view the advantage of being a single observer was the great freedom apart from the necessity of vigilance when the wind was moving towards the dangerous direction.

(*To be continued*)

551.552

Brief historical note on the formulation of Buys Ballot's Law

The name of Buys Ballot is to be found in almost every textbook of meteorology and his law of the relation of wind direction and pressure distribution is taught in the many schools which nowadays include elementary meteorology in their curriculum. It may therefore be of some interest to trace briefly the formulation of this law. Professor Buys Ballot, Director of the Dutch Meteorological Institute and Professor of Physics at Utrecht was amongst the pioneers in the use of synoptic meteorology for the issue of forecasts and storm warnings. In dealing with observations of pressure and temperature he made use of deviations from average values and in a paper presented to the Paris Academy of Sciences in 1857* he discussed the results obtained from observations at three stations in Holland. After showing that strong winds are indicated by large differences between the deviations, he proceeded to explain that if pressure was higher at Den Helder than at Maastricht (that is to say, higher in the north than in the south) then the wind was from the east while if pressure was higher at Maastricht the wind was from west or north-west. In the *Jaarboek* of the Meteorological Institute of the Netherlands for the same year (published in 1858) p. 347, this conclusion is stated in more general terms. Translated into English it reads 'great barometric differences, within the limits of our country, are followed by stronger winds, and the wind is in general perpendicular, or nearly so, to the direction of the greatest barometric slope in such a way that a decrease of pressure from north to south is followed by an east wind, and a decrease from south to north by a west wind'. In 1860 he published a paper entitled 'Eenige regelen voor aanstaande weersveranderingen in Nederland' (Some rules for approaching changes in the weather in the Netherlands), in which the law appears in its well-known form (pp. 50ff). 'Thus the rule for wind direction is this: if one places oneself in the direction of the wind with one's back to the place from which it is coming, then one has the lowest place (i.e. pressure) on the left-hand just as in the case of hurricanes'. (These storms had long been known to have a whirling motion and the distinction between the anti-clockwise rotation in the northern hemisphere and the clockwise rotation in the southern hemisphere had been expounded by Dove in 1828.)

[The above text, authorship unknown, is to be found in a pamphlet held in the National Meteorological Library and dated 1930.]

* Note sur le rapport de l'intensité et de la direction du vent avec les écarts simultanés du baromètre. *CR Acad Sci, Paris*, **45**, 1857, 765–768.

Review

Turbulent fluxes through the sea surface, wave dynamics, and prediction, edited by A. Favre and K. Hasselmann. 260 mm × 150 mm, pp. xiii + 677, *illus.* Plenum Publishing Corporation, New York, 1978. Price US $59.40.

This large volume contains the papers and discussions from a conference held in 1977 under the auspices of the NATO Air–Sea Interaction Program. The book has been prepared from the original papers by photographic means, so the standards of presentation are variable. The stated aim of both the conference and this book is to bring together specialist papers in the fields of air–sea interaction, wave dynamics, and wave prediction so that a cross-fertilization of ideas can take place. I should have liked to see more review papers in a publication with such an aim. However, for those with the necessary background, the quality of many of these papers is first class. The book is divided into four main sections dealing with: Fluxes through the air–sea interface; Non-linear dynamics of surface waves; Wind–wave interaction; and Numerical wave prediction models.

The first section deals mostly with the atmospheric boundary layer, describing a number of experiments both in the laboratory and in the field. The field experiments include a number from towers and some results from GATE. Of particular interest is a comparison of results from three methods of estimating surface fluxes.

The second section is the most comprehensive collection of papers on a variety of non-linear phenomena in surface waves known to the reviewer. It starts with an excellent review by Professor Longuet-Higgins of instabilities in steep waves. There are several other very good contributions on both weak and strong instabilities. Readers should, however, be warned of the complexity of much of the algebra. The review of bottom interaction which concludes this section is a particularly useful paper.

The third section deals mainly with observations of wave growth by wind action. However, it opens with a very interesting paper by Professor Phillips pointing out some of the dangers of extending laboratory results to the open sea. The papers that follow are nicely balanced between laboratory and field experiments along with two theoretical papers.

The final section on wave prediction models forms a useful survey of current work in this field, including papers on both the classical source function and parametric methods. The section opens with a very illuminating paper by Professor Hasselmann on the energy balance concept used in wave models.

B. W. Golding

Honour

The following honour was announced in the Birthday Honours List, 1979:

KNIGHT BACHELOR

Dr B. J. Mason, C.B., F.R.S., Director-General of the Meteorological Office.

Notes and news

The Ailsa Craig Experiment

Hearken, thou craggy ocean pyramid!
Give answer from thy voice, the sea-fowls' screams!

KEATS, *To Ailsa Rock*

Measurements of the airflow round the island of Ailsa Craig off the Ayrshire coast were obtained by members of the Boundary Layer Research Branch (Met O 14) from Porton, Cardington and Bracknell during a five week period in the autumn of 1978. Ailsa Craig was chosen because of its uniformly smooth shape and its relative isolation from any other features which could disturb the flow. Meteorological and domestic equipment was transported to the island by the Sea King helicopters of 819 Squadron, HMS *Gannet*. For most of the period a staff of four people was maintained on the island, with a VHF radio link to two further staff based at the meteorological office at Prestwick Airport.

The mean wind was measured by an array of anemographs mounted 4 metres above ground. The performance of the normal anemographs had been expected to be inadequate in areas of extreme turbulence and so three vector-averaging wind recorders, specially built at Porton, were used instead. Turbulence data were gathered by instruments supported by a tethered balloon which was launched from a small spit of flat land on the eastern side of the island by a balloon crew from RAE, Cardington. Unfortunately, severe turbulence in the lee of the island often made it impossible to fly the balloon, limiting the number of data collected.

In addition, the Hercules aircraft of the Meteorological Research Flight flew round the area on seven occasions during the experiment in order to measure relevant parameters—in particular the three components of the small-scale wind fluctuation—both upstream of the island (to obtain the 'undisturbed' flow) and also downstream to measure the horizontal and vertical extent of the turbulent wake. Flights were made along and across the wake at heights from about 30 m (very bumpy close to the island—patterns of disturbance could be seen on the sea) to about 1000 m, well above the island where the flow was usually quite smooth. It had been hoped that over the operating period a variety of wind directions and strengths would occur, but unfortunately the moist south-westerly type predominated and most of the flights were therefore in similar conditions.

Analysis of the data is still in progress, but a couple of preliminary results have emerged. The aircraft data consistently show a pronounced vortex downstream of the island with its axis of rotation pointing downwind. The vortex is very powerful, with vertical velocities of up to half the geostrophic wind, so that values of about ± 8 m s^{-1} were measured on occasions. The turbulence data from the tethered balloon show very large changes in the structure of the turbulence as it is distorted in passing round the sides of the island; in particular, the ratio of the turbulent energy components in the downstream and transverse directions is changed by a factor of about 10 from the usual boundary layer value.

(See Plates I–VI.)

Dr Aksel C. Wiin-Nielsen (Denmark) appointed Secretary-General of the World Meteorological Organization

The Eighth World Meteorological Congress, meeting in Geneva in May of this year, appointed Dr Aksel C. Wiin-Nielsen (Denmark) as Secretary-General of the World Meteorological Organization (WMO) for a period of four years commencing on 1 January 1980.

Dr Wiin-Nielsen, who is a graduate of the University of Copenhagen and holds a doctorate in meteorology from the University of Stockholm, was born in Denmark in 1924. In 1952 he joined the Danish Meteorological Institute. He was a member of the International Meteorological Institute in Stockholm (1955–58) and of the Joint Numerical Weather Prediction Unit in Suitland (USA) (1959–61).

From 1961 to 1963 he was the Assistant Director of the Laboratory for Atmospheric Sciences, National Center for Atmospheric Research in Boulder, Colorado (USA). Professor at the University of Michigan (1963–71) and later at the University of Bergen (1971–72), he was nominated Head of the Department of Atmospheric and Oceanic Science of the University of Michigan in 1972. In 1974 he was appointed Director of the European Centre for Medium-range Weather Forecasts near Reading (England). Dr Wiin-Nielsen is the author of numerous scientific papers on subjects in atmospheric dynamics, numerical weather prediction, atmospheric energetics and the general circulation of the atmosphere. He is also the author and the editor of several of the WMO training publications.

Dr Wiin-Nielsen is married and has three daughters.

Dr Wiin-Nielsen succeeds Dr David Arthur Davies, the present Secretary-General of WMO. Dr Davies was appointed to the office of Secretary-General in 1955 and has thus served in that capacity for 24 years, the longest period of service as Executive Head of any organization within the United Nations system.

Climatic variations: facts and causes, Erice, Sicily, 9–21 March 1980

The First International School of Climatology (Director, Professor A. Longhetto) will be held at the Ettore Majorana Centre for Scientific Culture, Erice, Trapani, Sicily from 9 to 21 March 1980. It will deal with Climatic Changes and Variations: Facts, Causes and Geophysical Background.

The main purpose of this course is to present a full review of palaeoclimatology, lectures being essentially oriented towards the physical basis of climatic changes and climatic variations.

This interdisciplinary course will provide an up-to-date survey of the most recent reconstructions of past climates and of the results of theoretical models simulating climatic changes and variations. Some lectures will also be devoted to man's impact on climate and a panel will discuss probabilities of climatic evolution in the next century.

This course is designed for people having a background in physical, mathematical, and geophysical or meteorological aspects of phenomena occurring in the climatic system. The program has been designed to provide information for researchers already working in this field as well as to stimulate and motivate all geophysicists engaged in developments related to climatic variations. Lectures will be delivered by 25 specialists who will review the following subjects: Mathematical and Physical Basis of Climate, Reconstruction of Past Climates, Causes of Climatic Variations, Modelling Techniques and Man's Impact on Climate.

Some fellowships available for travel and/or living expenses will be awarded on a competitive basis. The number of participants will be limited. For further information and applications, contact the Director of this course:

Professor A. Berger,
Institute of Astronomy and Geophysics,
Catholic University of Louvain,
Chemin du Cyclotron 2,
B-1348 Louvain-la-Neuve,
Belgium.

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