HOW FAR HAVE WE COME IN UNDERSTANDING THE DYNAMICS OF THE MIDDLE ATMOSPHERE?

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ABSTRACT

This lecture surveys two key aspects of the dynamics of global middle-atmospheric circulations and stratosphere–troposphere mass exchange rates, with their implications for temperatures (departing systematically from radiative equilibrium) and for the transport, distribution, and photochemical evolution of greenhouse gases. First, there is an overwhelming case that the tropical stratospheric quasi-biennial oscillation (QBO) is a wave-driven mean flow, though much uncertainty as to which waves are most important in driving it. The QBO is the most conspicuous illustration of the way in which wave fields can act "anti-frictionally", driving the atmosphere away from solid rotation, not toward it in the manner of a viscosity. Second, the global stratospheric (Brewer–Dobson) and mesospheric (Murgatroyd–Singleton) mean circulations are wave-driven. Nothing else can explain for instance the refrigeration of the summer polar mesopause; and nothing else is fluid-dynamically possible in a strongly stratified, rapidly rotating, radiatively relaxational atmosphere under anything like the observed conditions. This driving can be thought of as a mechanical "gyroscopic pumping". Again, there is uncertainty about exactly how the pumping action is shared between Rossby waves and gravity waves, and how this, and anti-frictional effects, might impact the robustness or otherwise of e.g. tropical stratospheric upwelling — the part of the system that "tape-records" the annual tropopause water-vapour cycle. The mesosphere has special importance not only as a sensitive detector of gravity-wave fields but also, potentially, of such things as long-term trends in water vapour and of poorly understood, or unsuspected, mechanisms related to solar variability.

1. INTRODUCTION

I greatly appreciate the honour of being invited to give one of the three Symposium Lectures to this community of scientists observing the real atmosphere. As a theoretical fluid dynamicist interested in the workings of the atmosphere (and as someone who should probably not be allowed too close to any critical experimental apparatus), I have long admired those who succeed in observing the real atmosphere with delicate, sophisticated and clever observing instruments, whether from the ground, from balloons or rockets, or from spacecraft. I am always astonished when any of these observing systems actually function as intended. It is obvious that there is a combinatorially large number of ways in which things can go wrong at any stage, especially when new technology is being deployed in a hostile environment. That successful measurements are obtained as often as they are seems to me to be some kind of miracle, and certainly a testimony to the courage and persistence, as well as the skill and ingenuity, of those who dare to try it against the odds.

I also find it amazing that we can *understand* anything at all about so complicated a system as the atmosphere. The complexity is becoming more and more apparent as the atmosphere is observed better and better. For instance Figure 1 overleaf, from Ref. [1], gives us a glimpse of the sort of fine-scale detail that is typical of so-called "vortical mode" motions. This example is on the 320 K isentropic surface and is part of what is involved in the exchange of mass and chemical constituents between the troposphere and lowermost stratosphere. Today there are very many such pictures in the literature, for various altitudes ranging up to somewhere near the stratopause though not, to my knowledge, in the mesosphere as yet. (For a small sample see, e.g., [Ref. 2, 3, 4, 5].) Such detail is surely wonderful yet frightening, especially when we remember that even finer detail must exist within the intermittent patches of three-dimensional, small-scale turbulence whose effects are noticeable from time to time when travelling in passenger aircraft. Figure 1 indicates how far we have come since the early 1980s, when I for one was trying to imagine, on the basis of much sparser observations, what real "vortical mode" flows might look like [Ref. 6, 7].

Figure 1 was constructed by methods that bring to data analysis a kind of theoretical and numerical-analytic

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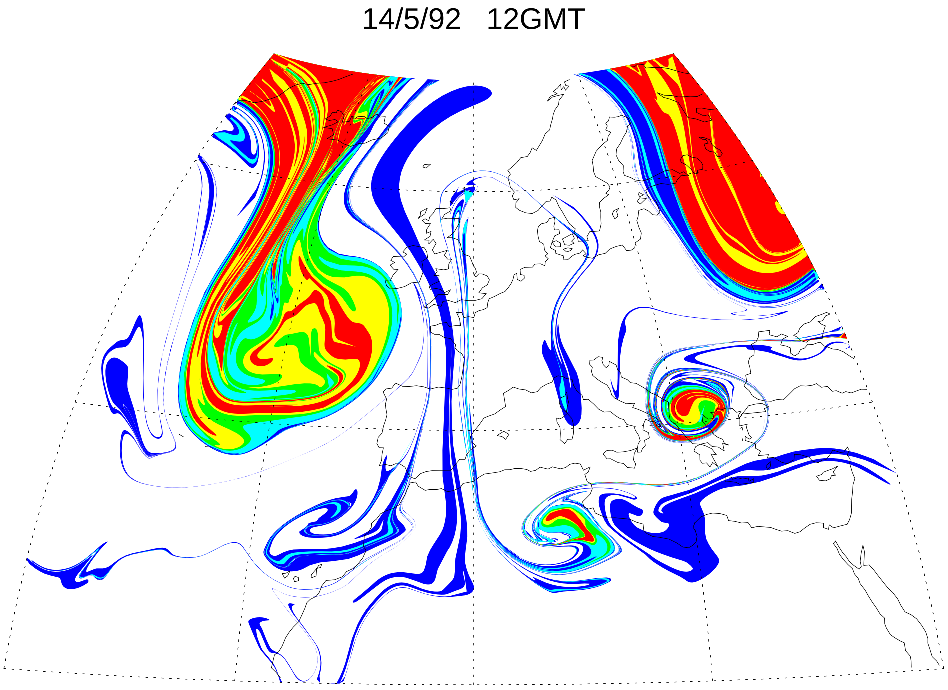

Figure 1: Hypothetical passive tracer on the 320 K isentropic surface for 14 May 1992 at 1200 Z, showing some of the vortical fluid motions involved in the exchange of air between stratosphere and troposphere, from Ref. [1]. Tracer advection was calculated by the contour-advection technique [Ref. 9, 10], using winds from the operational analyses of the European Centre for Medium Range Weather Forecasts initialized four days earlier to coincide with PV (potential vorticity) contours whose values are 1, 2, 3, 4, and 5, in the standard PV units of $10^{-6}\mathrm{m}^2\mathrm{s}^{-1}\,\mathrm{K}\,\mathrm{kg}^{-1}$, in a smoothed isentropic map of PV from the same operational analyses. Values from 1 unit upward are coloured rainbow-wise from dark blue to red, and represent nominally stratospheric air.

sophistication that before about 1994 was found only in the domain of "academic" fluid-dynamical studies [Ref. 8]. Such studies have given us highly accurate adaptive numerical algorithms for Lagrangian tracer advection by any given time-dependent velocity field. The particular algorithm used here is the one now called "contour advection" [Ref. 8, 9, 10]. The velocity field was obtained from an operational meteorological data-assimilation system, at the European Centre for Medium Range Weather Forecasts. In case you might think that no such fine detail could possibly be real — because of the relatively coarse spatial resolution of the velocity field — let me mention that in some similar cases instrumented aircraft have been flown across such filaments and have directly verified the corresponding jumps in chemical composition [Ref. 3, 11]. That is not saying that we can believe all the tiniest details, but it is saying that the pattern as a whole is likely to be much closer to reality than one might think, and qualitatively very realistic indeed [Ref. 10]. It is related to a classic point in fluid dynamics, the well known ability of simple straining flows — velocity fields of *infinite* spatial scale — to produce advected tracer features that shrink exponentially fast on the timescale of the strain rate [Ref. 12], thus producing features of arbitrarily *small* spatial scale.

(This leads to the classic random-straining models of turbulent tracer advection, the Batchelor spectrum and so forth [Ref. 13], whose extension to the kind of flow illustrated in Figure 1 (strongly stratified, layerwise-two-dimensional) has recently been carried out by Haynes and Anglade [Ref. 14], bringing in the vertical shear and thence Prandtl's ratio of scales f/N. Here N is the buoyancy frequency of the stratification and f the Coriolis parameter. It also reminds us that when thinking three-dimensionally we might prefer to imagine not filaments but sloping sheets of tracer — layers or laminae from a balloonist's perspective — whose intersections with an isentropic surface appear as thin filaments and whose typical or most probable slope $\sim f/N \sim 10^{-2}$.)

Now, in view of such a wealth of three-dimensional detail you might think that understanding — let alone quantifying — such things as the rates of mass exchange between stratosphere and troposphere must be a daunting task. It is indeed daunting in many ways. Yet we do have some significant, though imperfect, knowledge and understanding, as I hope to indicate in this lecture. We even have quite a good idea of the way in which stratosphere–troposphere exchange rates are strongly affected, indeed in a certain sense largely controlled, in the long-time mean, by what goes on well *above* the tropopause — quite independently of the complex detail *near* the tropopause illustrated by Figure 1.

A variation on the same theme is our understanding of how despite being about the sunniest place on earth the summer polar mesopause is also the coldest place on earth, and why there is enough water there to form the world's highest ice clouds, the famous and beautiful noctilucent clouds first observed in the 1880s [Ref. 15], along with related phenomena seen in radar, rocket, and satellite measurements and apparently involving hydrated ions [Ref. 16]. On a qualitative level we understand both the low temperatures and the replenishment of water vapour rather well — specifically, we can attribute them both to mean upwelling, and we understand what drives that upwelling — despite the complex detail that would probably be seen if we had mesospheric counterparts of Figure 1 that showed the vortical-mode motion over a large range of scales, intermingled with all the tidal and gravity wave activity. One of the essential points is that large-scale mean circulations at a given altitude, e.g. mean upwelling, are to a significant extent under the control of wave breaking and other wave-dissipation processes taking place *above* that altitude.

These examples, and other counterintuitive things like the influence of middle-atmosphere eddy dynamics on tropical tropopause temperatures [Ref. 17], are all beautiful examples of dynamical coupling in the middle atmosphere. And they are enough to tell us that in climate modelling, for instance, the middle-atmospheric component of the climate system needs to be taken seriously if only because of the vertical, and partly "downward", aspects of that coupling — the influence of things above — and the possibility of unwanted effects from artificial upper boundary conditions [Ref. 18, 19, 20].

2. SOME THINGS WE UNDERSTAND

Let me try to be a little more systematic. Here is a list of points about the middle atmosphere that are well understood by dynamicists today:

1. The quasi-biennial oscillation (QBO) is wave driven. (One of the most cogent arguments for this is the much neglected 1968 work of Wallace and Holton [Ref. 23]; I have discussed this point in [Ref. 24]. Like the Michelson–Morley experiment, the Wallace–Holton work illustrates the great importance of negative results in science. It made a strong case for an unknown kind of momentum flux as the only possible explanation of the observed zonal wind evolution, before wave driving was thought of.)

2. The global-scale Brewer–Dobson and Murgatroyd–Singleton circulations are wave driven, in a way that depends on Coriolis effects. This is the main control on long-time-average stratosphere–troposphere exchange rates, more precisely, on rates of mass exchange between the troposphere and the photochemically most active regions in the stratospheric "overworld" above the 380 K isentropic surface ($\lesssim 15\,\mathrm{km}$ altitude) [Ref. 18, 21, 22]. Similarly controlled are the rates of refrigeration and supply of water vapour to the summer polar mesopause.[Ref. 25]

3. The most important wave effects for these purposes are the irreversible fluxes or transports of momentum and angular momentum that arise when waves are generated in one place and dissipated in another. This is the missing ingredient adumbrated by Wallace and Holton (point 1 above).

4. The result is a global-scale distribution of small but inexorably persistent (ratchet-like) zonal or east–west zonal-mean forces $\overline{F}$ whose qualitative sense is largely independent of small-scale detail, even though their precise quantitative distribution within wave-dissipation regions usually depends on "wave breaking" events of various kinds. Here "wave breaking" is to be understood in the sense required by wave–mean interaction theory [Ref. 26].

5. The waves involved range from planetary-scale Rossby waves to small-scale gravity waves, in addition to the equatorially trapped hybrid wave types that also contribute to the QBO.

6. There is a tendency for $\overline{F}$ to act "anti-frictionally" in the sense of driving the system away from solid rotation. The QBO is the most conspicuous illustration of this phenomenon; here the anti-frictional behaviour arises from the simultaneous existence of prograde and retrograde phase speeds in the wave spectrum that produces $\overline{F}$ [Ref. 27, 28]. Conversely, no model QBO can be produced by an $\overline{F}$ parametrized as frictional, e.g. as a Rayleigh friction.

7. Another classic illustration of anti-frictional behaviour is what used to be called the "negative viscosity" associated with the large-scale eddy fluxes of angular momentum that show up in meteorological analyses [Ref. 29]. In this case Rossby-wave dynamics is involved [Ref. 30, 31], and the anti-frictional behaviour arises for very general reasons associated with the properties of potential vorticity [Ref. 24].

8. Typical magnitudes of $\overline{F}$, reckoned per unit mass in metres per second per day, appear to range over about three orders of magnitude from $\sim 10^{-1}\,\mathrm{m\,s^{-1}d^{-1}}$ in the lower stratosphere to $\sim 10^{2}\,\mathrm{m\,s^{-1}d^{-1}}$ or more near the mesopause, though we do not yet have a quantitatively satisfactory picture of real $\overline{F}$ distributions at all the relevant altitudes — even in terms of their climatology, let alone variability, especially

as regards the contributions from small-scale gravity waves.

9. The dynamical responses to such zonal forces, under the relevant parameter conditions, are of essentially two kinds [Ref. 32], depending mainly on the strength of Coriolis effects or, more precisely, on the so-called "inertial stability", proportional to the Coriolis parameter f times the large-scale latitudinal gradient $\overline{G}$ of specific absolute angular momentum about the Earth's axis. The first kind of reponse, characteristic of the lowest latitudes where $\overline{G}$ and f are small, is a gradual acceleration $\partial\overline{u}/\partial t$ of the zonal mean zonal wind $\overline{u}$, as seen in the QBO.

10. The second kind of reponse to $\overline{F}$ is a "gyroscopically pumped" mean meridional circulation, as seen in the Brewer–Dobson and Murgatroyd–Singleton circulations.

11. The gyroscopic pumping mechanism is explained in Figure 2 and its caption and depends on Coriolis forces or, more precisely, on inertial stability. It operates robustly away from the equator.

12. The circulation arising in response to the pumping action extends mainly below the altitudes at which the force $\overline{F}$ is applied, and to this extent may be said to be "downward controlled" (again see caption to Figure 2). However, there is also a tendency for the response to extend sideways, as well as downwards, into or across the tropics, and to do so persistently if the gyroscopic pumping is powerful enough. This involves nonlinear modification of $\overline{G}$ in the tropics [Ref. 18, 33, 34].

13. Under the typical parameter conditions in the lower stratosphere, "away from the equator" in point 11 means further than roughly $\pm 15°$latitude. More precisely and more generally, the pumping action and the "downward controlled" response to it operate robustly at latitudes where $f \neq 0$ and where $\overline{G}$ is too strong to be vulnerable to nonlinear modification. Conversely, the tendency of the response to extend sideways into a tropical region where $\overline{F} = 0$ depends on $\overline{G}$ being weak, hence nonlinearly modifiable, in that region.

    Other examples of gyroscopic pumping include the well known "Ekman pumping" in which the driving force $\overline{F}$ is provided by boundary friction rather than by waves, and certain other examples from solar physics [Ref. 35].

14. Solar heating does not directly drive the Brewer–Dobson and Murgatroyd–Singleton circulations. This is clear from the fluid-dynamical theory and associated thought-experiments. [Ref. 18, 36]. The point is also consistent, of course, with the observed equatorial, rather than polar, location of the real stratospheric upwelling at solstice, "despite" insolation being maximal at the pole. Numerical models exhibiting what appear to be global-scale circulations driven by solar heating depend on assuming that $\overline{F}$ has some kind of artificial frictional behaviour, usually Rayleigh-frictional.

15. The main effect of solar heating on middle-atmospheric circulations (beyond directly and indirectly maintaining various wave sources in the

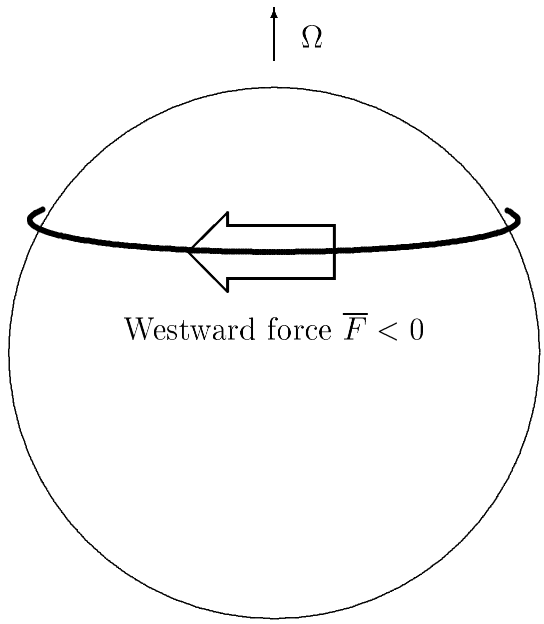

Figure 2: The gyroscopic pumping mechanism, in the case $\overline{F} < 0$ appropriate to all breaking Rossby waves and to gravity waves in the winter mesosphere. When a ring of air located away from the equator is pushed westwards, then Coriolis effects try to turn it poleward. This is a mechanical pumping action. The response to it has been studied by modellers, both numerically and analytically [Ref. 21, 22, 18], and exhibits the so-called "downward control" property: in a thought-experiment in which, in a radiatively relaxational atmosphere, an extratropical $\overline{F}$ is switched on in some range of altitudes $z \geqslant z_1$ and then left on, the circulation burrows downward below z_1 until it reaches the Earth's surface, where it closes off in a frictional boundary layer [Ref. 21, 22] and settles toward a steady state in which there is no meridional circulation above the range of altitudes where $\overline{F} \neq 0$. The steady state is approached fastest for broad $\overline{F}$ distributions over a large range of latitudes — usually, for practical purposes, somewhat faster than seasonal timescales. Ref. [21] gives a careful analysis and discussion of timescales and their relation to f^{-1}, N^{-1}, and radiative relaxation times.

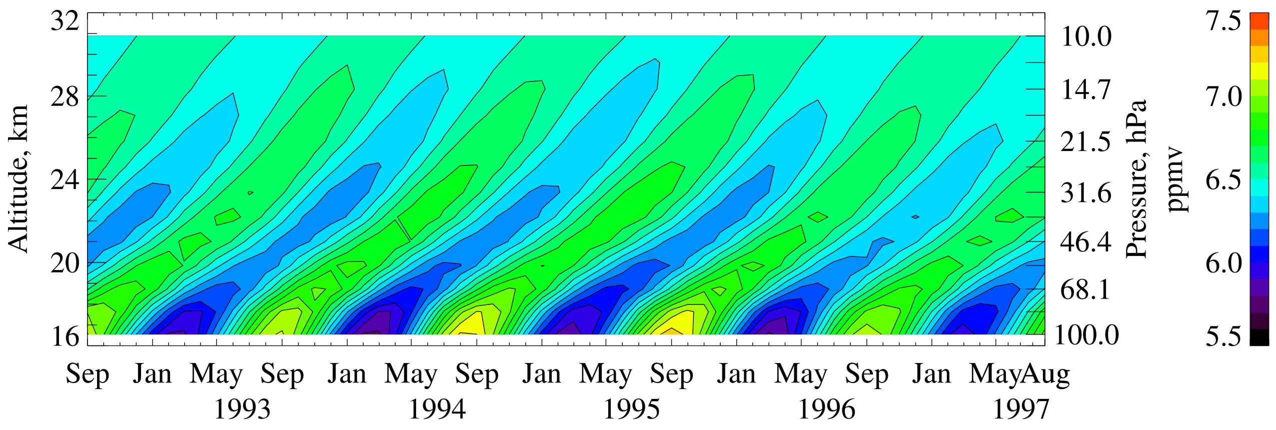

Figure 3: The tropical stratosphere as a 'tape recorder', from Ref. [42]; *q.v.* for a careful discussion of the data analysis and interpretation. The time-altitude plot is from HALOE, a solar occultation limb sounder on the Upper Atmosphere Research Satellite (UARS), showing the signal from the annual cycle in water vapor being advected upward by the large-scale mean velocity $\overline{w}$. Near 20 km, $\overline{w} \approx 0.2\,\mathrm{mm\,s^{-1}}$. Soundings between 14°N and 14°S were used. The quantity plotted is "total hydrogen", water vapor plus twice methane, in parts per million by volume. Because of methane oxidation chemistry this is to excellent approximation a passive tracer in the altitude range shown. The raw data have been fitted to a suitable set of extended empirical orthogonal functions (EEOFs) to extract the annual cycle in an objective way; the plot shows the contributions from the dominant two EEOFs, accounting for 68% of the variance. But the tape-recorder signal is still easily visible without any such processing — see Plate 1 of Ref. [42] — and in data from other instruments, notably the passive Microwave Limb Sounder on UARS [Plate 1a of Ref. 43].

troposphere) is to influence the height–latitude distribution of radiative equilibrium temperatures $T_{\rm rad}$ in the middle atmosphere. This in turn affects zonal wind shears in thermal-wind balance, hence wave refraction and "filtering" — e.g. making eastward-propagating waves break sooner than westward-propagating ones — impacting the height–latitude distribution of $\overline{F}$ and hence the global-scale distribution of gyroscopic pumping. For instance the Murgatroyd–Singleton circulation at solstice owes its existence to the strong selective filtering of upward-propagating gravity waves by the stratopause jets below, making $\overline{F}$ westward in the winter and eastward in the summer hemisphere [E.g. Ref. 37, 38 & refs. therein]. This pumps air very powerfully in the summer-to-winter direction, in both hemispheres, at altitudes near the mesopause.

16. Solar heating has an entirely different and more subtle effect in the tropical stratosphere. It influences the precise *pathway* of the tropical stratospheric upwelling, tending, to a varying extent, to channel it toward the summer side of the Equator at solstice. Gyroscopic pumping still largely controls the net mass flux drawn up from the tropical troposphere, but the geographical distribution of upwelling is influenced by the geographical distribution of $T_{\rm rad}$ in the tropics. This is a dynamical regime quite unlike the free, tropically-confined Hadley convection that would take place in some equatorial latitude band if the gyroscopic pumping were switched off [Ref. 39, 40, 41]. The distinction becomes clearest in models avoiding the assumption — often incorrect, as I have been at pains to emphasize — that $\overline{F}$ has frictional behaviour.

3. THE TAPE-RECORDER ANALOGY

I like to think of the Brewer–Dobson circulation as a kind of tape recorder. This idea is beautifully illustrated by Figure 3, taken from Ref. [42], which shows the annual cycle in tropical-tropopause water vapour mixing ratio being carried up in the rising branch of the Brewer–Dobson circulation, like a signal being written to a moving tape by a "recording head" at the tropopause.

This tape recorder is not a very high quality one. For instance, the signal attenuates rather severely with height; Ref. [42] analyzes this quantitatively. The tape speed is so slow, a few tenths of a millimetre per second, of the order of a scale height per year, that even a small rate of lateral mixing across the subtropical "eddy-transport barrier" [Ref. 18, §4] can attenuate the signal significantly.

So too can a small vertical diffusivity K_z, even smaller than some of the classic estimates of order $K_z \sim 2 \times 10^{-1}\,\mathrm{m^2s^{-1}}$. In fact, Ref. [42] finds that the remarkably weak attenuation of the tape-recorder signal in Figure 3 at altitudes around 20 km demands K_z values as low as $K_z \sim 2 \times 10^{-2}\,\mathrm{m^2s^{-1}}$.

But Figure 3 is a striking confirmation — yet one more consistency check — on the general picture of the mean circulation that for some time has been clear from several independent lines of evidence. As is well known, these are (a) other information about chemical tracers [E.g. Ref. 2, 44 & many refs. therein], (b) estimates of the circulations from state-of-the-art radiation schemes and observed temperatures [E.g. Ref. 45, 46, 47], and (c) a combination of dynamical observations, theory, and numerical modelling, including diagnostic estimates of the global $\overline{F}$ distribution due to Rossby waves together with (as yet rather crude) estimates of the gravity-wave contribution [E.g. Ref. 37, 46, 48].

In the tape-recorder analogy, with gyroscopic pumping acting as the "motor" of the tape drive, the tropical distribution of T_{rad} is to be thought of as a system of "guidance wheels" (point 16 of §2), having an influence on the pathway taken by the tape but not on the net throughput. One might say that the sun shifts the tropical "guidance wheels" back and forth but does not directly power the "motor".

Alternatively, one may think of regions of high T_{rad} in the tropics as like the deeper channels in a river bed, in some location where the river is flowing quietly, away from the rapids: flowing subcritically, that is, in the language of hydraulics. In such a region of subcritical flow, depth variations influence the path taken by the water but not the total flow rate. The total flow rate is determined in an entirely independent way, by conditions upstream, most immediately by the nearest upstream location of hydraulic control, such as a weir. Dredging the river bed to make one of the channels deeper makes not the slightest difference to the total flow rate, though it may well cause the flow to be locally stronger at the expense of being weaker elsewhere.

4. SUBTROPICAL SENSITIVITY

Of course such analogies have their limitations, and the Brewer–Dobson circulation is indeed not quite as simple as a tape recorder, or even a river, in all of its aspects. There are some serious fluid-dynamical technicalities here. Indeed, some aspects are only beginning to be understood by dynamical researchers. These have to do with the nonlinear modification of $\overline{G}$ in the tropics (points 12 and 13 above).

Gyroscopic pumping works most effectively when the force $\overline{F}$ producing it is distributed over a sufficiently broad latitude band in the extratropics. In particular, the westward force distribution $\overline{F} < 0$ needs to extend sufficiently close to the Equator if it is to drive Brewer-Dobson cells that pull air up from the tropical troposphere as observed, rather than from higher latitudes. Just how close to the Equator, and whether there is any associated non-robustness, is unclear and is still being researched by dynamicists [Ref. 33, 34].

Some idealized models carry suggestions of non-robustness in the form of hysteretical behaviour, in thought-experiments in which $\overline{F}$ is prescribed to be zero in some tropical band and westward at higher latitudes. Through nonlinear modification of $\overline{G}$, one and the same $\overline{F}$ distribution can drive two different steady-state regimes of circulation. In the first of these, the pumping action pulls air up from the tropical troposphere throughout a broad cross-equatorial latitude band, somewhat as observed. In the second, the air is pulled up from a narrower latitude band in the subtropics, much closer to the latitude where $\overline{F}$ goes to zero.

However, such hysteretical behaviour has yet to be demonstrated in a general circulation model, and is not even exhibited by all models that might qualify as idealized stratospheres [Ref. 33]. All we can say for now is that there might well be a significant sensitivity of the tropical and subtropical branches of the Brewer–Dobson circulation to small wave-induced forces $\overline{F}$ in subtropical latitudes.

Significant $\overline{F}$ values for this purpose are well below the present threshold of observational constraints on, say, gravity wave drag. Again, we are talking about numbers $\sim 10^{-1}\,\mathrm{m\,s^{-1}d^{-1}}$ for $\overline{F}$. The weaker the inertial stability, the smaller the $\overline{F}$ required. What counts is long-time average $\overline{F}$ values, over months or longer. An educated guess would say that both Rossby and gravity waves are likely to be significant for this purpose, though in unknown proportions. And, as far as I know, the possible implications of "anti-frictional" $\overline{F}$ behaviour have not yet been considered at all.

5. MESOSPHERIC SENSITIVITY

We should not underestimate the potential importance of understanding the mesosphere better. It exhibits observable phenomena that are sensitive to what goes on below, and hence to what comes up from below, most conspicuously the supply of water vapour and the flux of gravity waves [E.g. Ref. 49]. And there is also the question of what comes in from above. Photochemical products modulated by solar variability on a range of timescales, through the solar wind and through hard ultraviolet, can be carried deep down into the ozone layer by the winter branch of the mean circulation, and, as is now increasingly discussed, may significantly affect ozone and radiation, complicating the issue of solar effects on climate change [E.g. Ref. 50, 51].

So observations of the mesosphere may well be recognized, sooner or later, as an important part of our repertoire of means to monitor and simulate global environmental change. Gravity waves in particular have tended up until now to be viewed as unimportant by climate researchers, who are rightly worried by more conspicuous effects like ocean–atmosphere, cloud–radiation and geosphere–biosphere interactions; but I hope that this lecture has illustrated why gravity waves need to be taken seriously. Our shaky knowledge of real wave fields implies that we have a correspondingly shaky knowledge of the dynamics of the Brewer–Dobson and even more the Murgatroyd–Singleton circulation, and therefore no assurance that such circulations — and their robustness or non-robustness against change — are being represented in a causally correct way in general circulation models. Yet we already know very well that those circulations are crucial to the ways in which greenhouse gases are moved around and chemically transformed.

Let me stress that our theoretical understanding of gravity-wave *sources* is even worse than our observational knowledge of them. For instance we have little idea how important or otherwise gravity wave emission from tropopause jets might be, or whether the observed correlation with tropopause jet-stream activity is mainly due to the correlation of such activity with surface winds and with orographic, and frontal, gravity-wave generation. A few theoreticians like myself have worried quite a lot about jet emission without getting very far. There are two conceivable mechanisms that might send gravity waves from tropopause jets into the high stratosphere and mesosphere.

One is 'Kelvin-Helmholtz envelope radiation' from the shear layer above a tropopause jet [Ref. 52]. The other is the spontaneous-adjustment emission, or "Lighthill radiation" [Ref. 53], of low frequency inertia–gravity waves by unsteady jet-streak events near the tropopause. Both of these processes are extraordinarily hard to model convincingly, either numerically or theoretically. There are no small parameters that give nice asymptotic theories where one can precisely understand what is going on. Numerics is demanding, with a premium on very fine resolution to describe the jet-streak dynamics accurately, and more than a suspicion that some of the results obtained so far in the literature could well be numerical artefacts. This is an ongoing area of research where we do not have many answers yet. So observational case studies that associate stratospheric and mesospheric gravity waves with tropopause jets will continue to be enormously valuable, especially over flat land or oceans.

Also still poorly understood is the problem of vertical mixing by mesospheric gravity-wave breaking. I convinced myself in 1989, through a simple but rather clear-cut thought-experiment [Ref. 25], that, because mesospheric wave breaking tends to be convective and not shear-driven, the usual formula

$$K_z = \beta\varepsilon/N^2 ,$$

where ε is turbulent dissipation per unit mass, and β a dimensionless number, is not useful in this case (even though it may be useful for some cases of mechanically or shear-driven turbulence). It turns out that β and turbulent Prandtl numbers are hopelessly sensitive to the *degree of wave supersaturation* — whether the breaking is violent, as on a steep ocean beach, or gentle as on a shallow beach. And the whole thing is sensitive to initial-condition noise. In trying to quantify real vertical mixing in the mesosphere and lower thermosphere, we are going to remain heavily dependent on observations of the real mixing of atomic oxygen and other tracers.

Measurements of ε are still extremely useful, of course, in their own right, because they provide important observational constraints on theoretical attempts to model gravity waves and gravity wave breaking.

Yet another unanswered question, though one on which some progress is being made, is whether mesoscale diabatic heating patterns from cumulonimbus convection could possibly be the dominant source of gravity waves from such convection. If so, we can use linear gravity–wave generation theory, given the diabatic heating [E.g. Ref. 54, 55, 56], about which heating the various GEWEX-associated projects are giving us increasing amounts of information. Again, observational case studies of the resulting mesospheric gravity waves, especially, should continue to be enormously valuable here.

I like Gary Thomas' analogy of the "miners' canary". It is well known that coal miners used to take a canary in a cage down with them because the bird was more sensitive than humans to small amounts of dangerous methane. Similarly, the mesosphere with its sensitivity to what goes on below, as well as above, could serve humanity as an early warning of new danger to its global environment, just as the polar stratosphere has already done, and in a totally unforeseen way. Who knows where the next signal will come from? Will it be terrestrial or extraterrestrial?

6. POSTLUDE: PUBLIC UNDERSTANDING

Good scientific research is, and has always been, like driving in the fog; and scientific observing instruments are our eyes and ears on an uncertain future. When new data emerge from the fog of uncertainty, it would be irresponsible not to consider changing direction as necessary, and irresponsible not to go slowly even if no obstacle is visible — the relevant "precautionary principle", as it is now called. Will the sea level rise by 2 m over the next century? On present knowledge that may seem improbable; but it is not impossible.

People and organizations who say that there is no need to worry about global environmental change are therefore showing, I would argue, exactly the same kind of irresponsibility as a bus driver who shuts his or her eyes in the fog, turns up the volume on the Walkman, and steps on the gas — except that the passengers at risk are now the entire population on Earth. The same irresponsibility is shown by telecommunications interests that threaten to jam the electromagnetic spectral windows crucial to terrestrial and extraterrestrial observation.

Scientists as a community are in trouble today, for many complicated reasons [Ref. 57]. I think one of them is that a small minority of scientists, among others, have talked too long and loudly about Absolute Control and Absolute Truth — as with the talk about Designer Babies, Knowing the Mind of God, etc. — showing insufficient respect for that greater reality, scientific uncertainty, which is combinatorially large. Our changing planetary environment has already taught us, the human species, new respect for scientific uncertainty, and is likely to continue to do so. That an observed reality, the Antarctic ozone hole, should have persuaded a major multinational industry to change course was something entirely new, something politically impossible in our culture until very recently.

Those who take the trouble to observe the atmosphere carefully, and other parts of the planetary life support system on which we depend, are in my opinion doing one of the most important things a human being can do. Let us have the courage, then, to keep our eyes and ears open.

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