Downloaded from rsta.royalsocietypublishing.org

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

# Current Understanding of Mesospheric Transport Processes [and Discussion]

Susan Solomon, R. R. Garcia and M. E. McIntyre

*Phil. Trans. R. Soc. Lond. A* 1987 **323**, 655-666
doi: 10.1098/rsta.1987.0112

**Email alerting service** Receive free email alerts when new articles cite this article - sign up in the box at the top right-hand corner of the article or click **here**

To subscribe to *Phil. Trans. R. Soc. Lond. A* go to: **http://rsta.royalsocietypublishing.org/subscriptions**

This journal is © 1987 The Royal Society

Downloaded from rsta.royalsocietypublishing.org

*Phil. Trans. R. Soc. Lond.* A **323**, 655–666 (1987)
*Printed in Great Britain*

# Current understanding of mesospheric transport processes

By Susan Solomon[1] and R. R. Garcia[2]

[1] *National Oceanic and Atmospheric Administration, Aeronomy Laboratory, Boulder, Colorado* 80303, *U.S.A.*

[2] *National Center for Atmospheric Research, Boulder, Colorado* 80307, *U.S.A.*

The chemistry and transport processes taking place in the mesosphere (approximately 50–85 km altitude) are strongly coupled. In recent years, the physical mechanisms influencing the transport processes of the mesosphere have become better understood, through both theoretical and observational studies. Perhaps most importantly, a theoretical framework for describing the momentum deposition and diffusion due to breaking small-scale gravity waves has been developed and shown to result in thermal, chemical and dynamical structure that closely resembles observations. The transport due to planetary waves and tides has also been the subject of study. In this paper, the transport processes influencing mesospheric distributions of chemical constituents are briefly reviewed.

## 1. Introduction

It is well known that the chemistry of the mesosphere is considerably simpler than that of its neighbouring region, the stratosphere. The intense solar-radiation field of the mesosphere precludes the existence of relatively weakly bound, large molecules such as $HNO_3$ and $ClONO_2$, which play prominent roles in stratospheric chemistry. In contrast, the chemistry of the mesosphere is dominated by atomic species and strongly bound, small molecules.

The intense radiation field that determines this chemistry also provides a substantial source of heat, which in turn influences the circulation of this region. Further, a considerable body of evidence points toward the important role that small-scale breaking gravity waves may play in producing the turbulent diffusion and driving the mean meridional circulation of the mesosphere (Lindzen 1981; Matsuno 1982; Holton 1982, 1983). The associated transport of mesospheric chemical species such as $H_2O$ and NO plays an essential role in determining the distributions of these constituents; indeed, in spite of the rapid photochemical environment that characterizes the mesosphere, transport processes cannot be neglected when considering the elements that determine mesospheric chemical composition.

The intent of this paper is to briefly describe the transport and photochemistry that determines the distributions and variability of mesospheric constituents. An exhaustive review of the literature on these subjects is beyond the scope of the present paper, and the selected references are intended to serve only as representative examples. The physical processes leading to small-scale turbulence and its influence on transport of chemical species will be summarized and compared to the transport processes associated with the much larger scale mean-meridional circulation. The local effects of planetary waves in the winter mesosphere and the role of tides in modulating mesosphere photochemistry and gravity-wave breaking will also be explored.

The Royal Society is collaborating with JSTOR to digitize, preserve, and extend access to
*Philosophical Transactions of the Royal Society of London. Series A, Mathematical and Physical Sciences.*
www.jstor.org

Downloaded from rsta.royalsocietypublishing.org

## 2. Mesospheric turbulence

It has long been suspected that the principal source of turbulent mixing in the mesosphere is the breakdown of small-scale gravity waves that originate largely in the troposphere. Breaking gravity waves also constitute an important source of zonal mean momentum in the mesosphere, that helps drive the mean meridional circulation of this region. We discuss this issue in §3. Likely sources of gravity waves include tropospheric flow over surface topography, thunderstorms, and frontal zones. Depending upon their amplitude, such waves can propagate to the mesosphere, growing exponentially with altitude until they become convectively unstable and 'break', producing turbulent mixing of chemical species (Hodges 1969; Hines 1970; Lindzen 1971; Jones & Houghton 1972; Lindzen 1981; Schoeberl *et al.* 1983; Garcia & Solomon 1985). An important factor influencing the vertical propagation of such waves to the mesosphere is the underlying stratospheric zonal-wind distribution. In particular, upward-propagating gravity waves may encounter critical levels in the stratosphere (where the local zonal-wind velocity equals the phase velocity of the wave) and become absorbed. Because the zonal winds in the stratosphere vary substantially with season, latitude, and even longitude, the propagation of gravity waves to the mesosphere will likewise be subject to considerable variability depending upon the underlying stratospheric wind system through which they must pass (Dunkerton & Butchart 1984; Schoeberl & Strobel 1984). Further, the intensity of vertical diffusion generated by a breaking gravity wave can be shown to be related to the meridional gradient of solar heating, which is also subject to considerable seasonal and latitudinal variation (Garcia & Solomon 1985). The limitations of linear theory in quantitative prediction of the eddy fluxes associated with gravity-wave breaking continue to be the subject of numerous studies. For example, Chao & Schoeberl (1984) and Fritts & Dunkerton (1985) have argued that the localization of the convectively unstable region leads to much smaller estimates of the eddy fluxes of heat and constituents than those obtained assuming that turbulence acts uniformly on the entire wave. (See also the review by Fritts (1984) for a thorough discussion of this and a number of related topics concerning gravity-wave saturation.)

Radar echoes provide an indirect means of inferring the location and intensity of vertical diffusion at mesospheric altitudes (Balsley *et al.* 1983; Vincent & Reid 1983). Such data confirm that substantial seasonal variations in the strength of turbulent diffusion occur, in approximate agreement with theoretical expectations (Lindzen 1981). Figure 1*a*, *b* depicts the seasonal variations of radar echoes observed at Poker Flat, Alaska, and the height profiles of signal-noise ratio in summer and autumn, suggesting a narrow turbulence profile peaking near 90 km in summer, and a much broader profile maximizing at about 70 km in winter and autumn. Of particular interest are the pronounced minima in the calculated and inferred diffusion near the spring and autumn equinoxes at middle and high latitudes (figure 1*c*).

The role of turbulent transport in determining the distributions of mesospheric chemical species is closely tied to the photochemistry of the mesosphere. Near the stratopause, most of the solar radiation available to drive photochemical effects lies in the wavelength range above about 200 nm (corresponding to bond strengths of less than 150 kcal mol$^{-1}$). At the mesopause, on the other hand, substantial amounts of radiation at wavelengths as short as Ly-$\alpha$ become available (121 nm, or chemical bond energies of less than 230 kcal mol$^{-1}$). Thus a sharp gradient in available photon energies exists between the stratopause and the mesopause. This in turn can lead to large vertical gradients in the rates of formation and destruction of

Downloaded from rsta.royalsocietypublishing.org

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

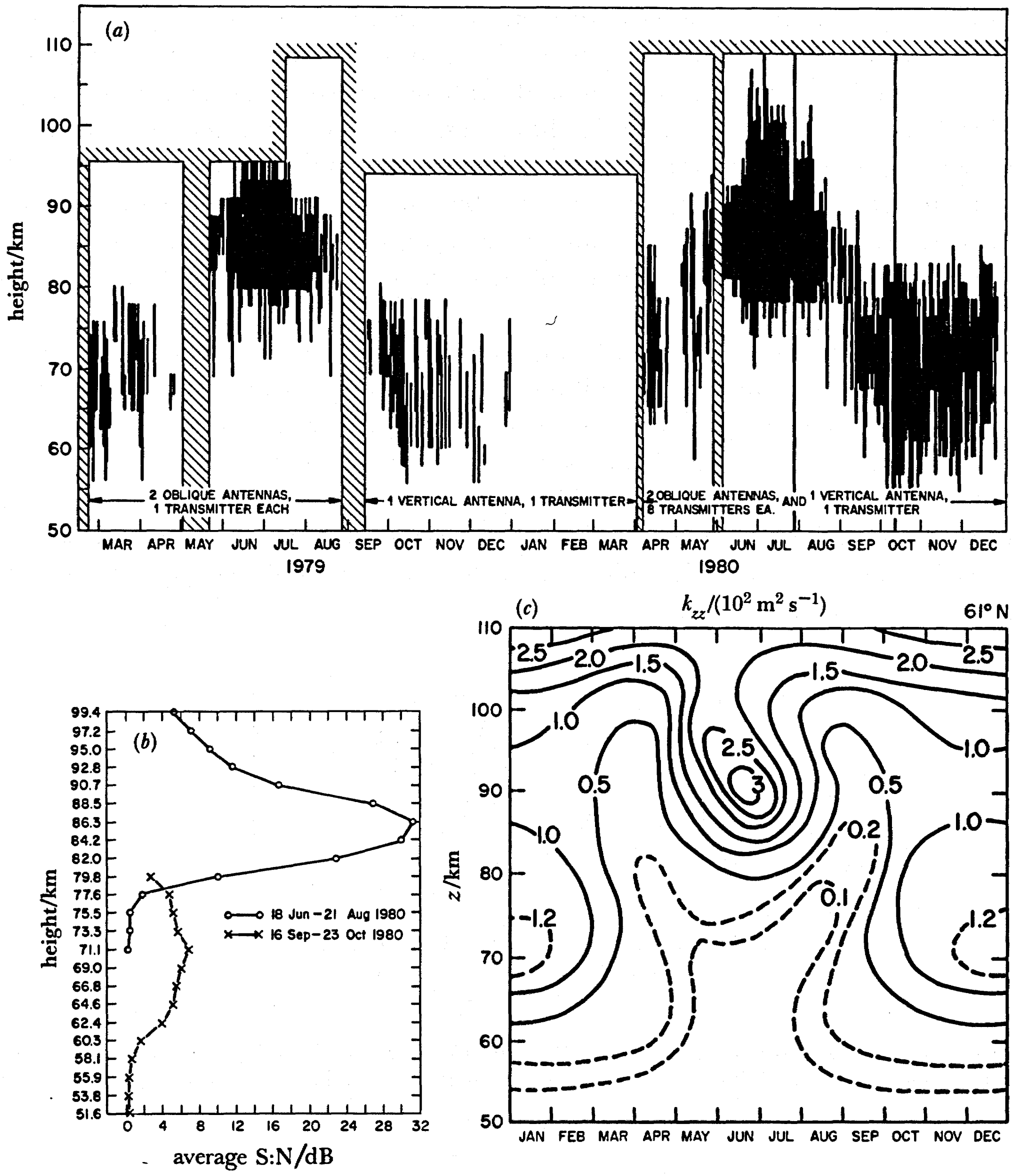

FIGURE 1. (*a*) Height distribution of MST radar echoes at Poker Flat, Alaska, (65° N) as a function of season. Cross-hatched areas denote periods and altitudes for which no data are available (from Balsley *et al.* 1983). (*b*) Vertical profiles of radar echo signal:noise ratio for summer (average from July 18 to August 21, 1980) and autumn (average from September 16 to October 23, 1980), from Balsley *et al.* (1983). (*c*) Computed vertical profile of eddy diffusion coefficient as a function of season for 61° N, from the model of Garcia & Solomon (1985).

chemical species. Atomic oxygen, carbon monoxide, and water vapour all have substantial vertical gradients in their photochemical lifetimes and in their profiles; thus these and other constituents depend sensitively on the rate of vertical mixing in the mesosphere (Allen *et al.* 1981, 1984). Variations in vertical mixing may be expected to lead to important variations in the distributions of these constituents; indeed, observed variability in mesospheric water vapour abundances is not readily explained without invoking the role of vertical diffusion (Bevilacqua *et al.* 1983). The chemical lifetime of water vapour is of the order of several months near the stratopause but only a few days near the mesopause. There is no significant chemical

Downloaded from rsta.royalsocietypublishing.org

source of water vapour in the mesosphere or thermosphere, so that the mesosphere is a region of net destruction of water vapour. The fast decrease in its lifetime with increasing altitude implies that this species is highly dependent on the rate of its vertical transfer. Atomic oxygen, on the other hand, is produced rapidly in the mesosphere and lower thermosphere, where sufficient energy is available to rapidly break the strong bond of molecular oxygen. It is efficiently destroyed near and below the mesopause by catalytic cycles involving hydrogen free radicals (Allen *et al.* 1984). Thus its distribution is also quite sensitive to the rate of vertical transfer from the source region in the thermosphere to the sink region below (Elphinstone *et al.* 1984; Garcia & Solomon 1985).

Perhaps the most striking evidence available to date regarding the importance of seasonal and latitudinal variations in mesospheric diffusive transport and chemical species distributions is provided by the ozone observations from the Solar Mesosphere Explorer (SME). Thomas *et al.* (1984) showed that the ozone abundance near 80 km undergoes a repeatable and unexpected seasonal cycle, with maximum abundances in spring and autumn and minima in winter and summer, as shown in figure 2. This behaviour is likely because of seasonal variability in mesospheric diffusion through its influence on the transport of water vapour and atomic oxygen (Garcia & Solomon 1985).

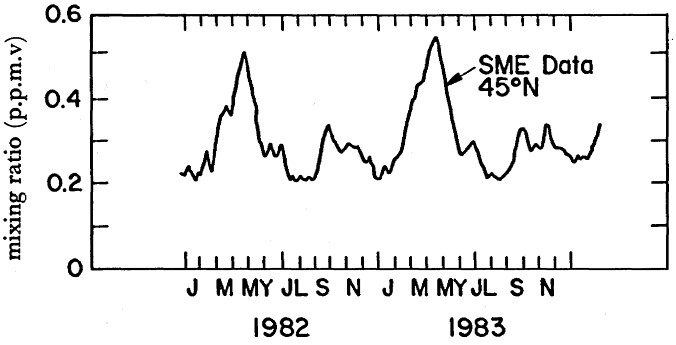

FIGURE 2. Seasonal variation of ozone observed at 0.01 mbar, 45° N, by the Solar Mesosphere Explorer satellite during 1982 and 1983, from Thomas *et al.* (1984). The units of the mixing ratio are parts per million by volume.

## 3. THE MEAN MERIDIONAL CIRCULATION OF THE MESOSPHERE

Radiative balance considerations demonstrate that the mesosphere must be characterized by a vigorous mean meridional circulation. In contrast to the stratosphere, the mesospheric temperature distribution displays remarkable departures from expectations based purely on radiative grounds. For example, the summer polar mesopause temperature is only of the order of 140 K, whereas that of the winter mesopause is about 210 K. Because the summer polar mesopause is subject to solar heating 24 hours per day, whereas the winter mesopause is in complete darkness for a period of months, these temperatures must be determined by processes that are not radiative. The principal terms in the thermodynamic equation may be written as (Dunkerton 1978)

$$\bar{w}^*(HN^2/R + \mathrm{d}\bar{T}/\mathrm{d}z) = \bar{Q}, \tag{1}$$

where $HN^2/R$ is the global mean static stability, $\bar{Q}$ is the net radiative heating rate, $\bar{w}^*$ is the mean vertical wind velocity and $\bar{T}$ is the zonally averaged deviation from the global mean

Downloaded from rsta.royalsocietypublishing.org

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

temperature. This equation shows that the temperature depends not only on the net radiative heating, but also on the vertical velocity. Upward velocities are associated with adiabatic cooling whereas downward velocities lead to adiabatic compression and warming. Thus the observed mesospheric temperatures are consistent with a mean circulation characterized by upward motion in summer and downward motion in winter that is sufficiently strong to reverse the temperature distribution due to radiative processes (Murgatroyd & Singleton 1961; Leovy 1964; Houghton 1978).

An important question raised by these considerations is what mechanisms are responsible for driving such a strong meridional circulation. Although planetary waves may play a role in forcing the mean circulation of the winter hemisphere (see §4), they cannot account for the intense circulation needed near the summer pole. Further, the mesospheric gradient of solar heating is not sufficient to drive a circulation of the required magnitude even in the presence of strong frictional dissipation of zonal momentum (Leovy 1964; Schoeberl & Strobel 1978; Holton & Wehrbein 1980). Recent studies (Holton 1982, 1983; Matsuno 1982; Garcia & Solomon 1985) have shown that the momentum deposited by small-scale breaking gravity waves is quantitatively consistent with the momentum source required to drive a very strong meridional circulation. Theoretical calculations of mesospheric temperatures and zonal wind distributions are in general agreement with observations when gravity-wave dissipation is used to drive the mesospheric circulation in a two-dimensional model framework. Further, a self-consistent representation of the diffusive and advective transport processes of the mesosphere follows from the theoretical analysis of the dynamics of breaking gravity waves (Lindzen 1981). Equation (1) illustrates the close coupling between net radiative heating ($Q$) and the mean meridional circulation. As yet, however, calculations of mesospheric dynamics have not been performed with detailed non-local thermodynamic equilibrium (NLTE) calculations for the radiative budget, nor have the sources and phase speeds of tropospheric waves been adequately characterized.

The mean meridional circulation of the tropical lower mesosphere is also a subject of interest. Recent studies (Dunkerton 1982) have shown that the semiannual oscillation of the tropical mesopause is probably linked to the dissipation of gravity and Kelvin waves. Transport of methane and nitrous oxide in the lower mesosphere exhibits a semiannual oscillation that is believed to be related to this dynamical forcing (Gray & Pyle 1986).

Observations of atomic oxygen and of the $O/O_2$ ratio clearly reveal the need for a strong mean circulation in the lower thermosphere, with flow from the summer to winter hemispheres (Kasting & Roble 1981, and references therein). Clear evidence for a large-scale mesospheric circulation is provided by observations of carbon monoxide. Carbon monoxide is produced largely in the lower thermosphere by photolysis of carbon dioxide, and destroyed in the sunlit mesosphere by reaction with OH. The short lifetime of carbon monoxide at mesospheric altitudes (order of a week) and this distribution of sources and sinks implies that it should be quite sensitive to mesospheric transport (Hays & Olivero 1970), particularly in the polar-night region where chemical loss with OH does not take place. Chemical theory alone suggests that the abundance of carbon monoxide should be greatest in summer, when its production by photolysis of carbon dioxide is most rapid. Observations reveal the opposite seasonal trend, suggesting that the transport of carbon monoxide must be important (Clancy *et al.* 1982, 1984; Murphy 1985). Quantitative study of the chemistry and transport of the carbon monoxide in a two-dimensional model reveals variations similar to those observed (Solomon *et al.* 1985).

Downloaded from rsta.royalsocietypublishing.org

The source region and transport of nitric oxide are quite similar to those of carbon monoxide in the mesosphere. Nitric oxide is produced rapidly in the lower thermosphere, where sufficient energy is available to break photochemically the extremely strong bond of molecular nitrogen (the CIII solar line at 99.7 nm is particularly effective in the process, as are energetic electrons produced both by aurorae and by solar radiation). The atomic nitrogen produced (particularly in the excited $^2D$ and $^2P$ states) can then react with oxygen to form NO. In the sunlit mesosphere, NO is destroyed by

$$\mathrm{NO} + h\nu \rightarrow \mathrm{N}(^4\mathrm{S}) + \mathrm{O},$$

followed by

$$\mathrm{N}(^4\mathrm{S}) + \mathrm{NO} \rightarrow \mathrm{N_2} + \mathrm{O}.$$

Thus, like carbon monoxide, nitric oxide has a strong thermospheric source, a rapid loss rate (timescale of the order of days) in the sunlit mesosphere, and a strong dependence on the rate of vertical transfer by the mean meridional circulation. Very low nitric oxide abundances are observed near the summer mesopause where the mean circulation is directed upward from the nitric-oxide-poor lower mesosphere (Swider 1978). In the polar-night region, where there is no chemical loss of nitric oxide (and a substantial source exists in the auroral regions) large abundances of nitric oxide can be produced in the thermosphere and transported downward to the lower mesosphere and upper stratosphere (Frederick & Orsini 1981; Solomon *et al.* 1982; Brasseur & DeBaets 1986). Observations by satellites (Russell *et al.* 1984) and by rockets (Horvath *et al.* 1983) clearly show that substantial large-scale, downward transport of nitric oxide occurs in the polar-night mesosphere.

It is important to consider how the transport by the mean meridional circulation competes with the diffusive transport by breaking small-scale gravity waves discussed earlier. The strength of the mean meridional circulation should be greatest near the poles (Holton 1982), and the transport by the mean circulation is thus likely to be of greatest importance at high latitudes (LeTexier *et al.* 1987). Further, the competition between diffusive and advective transport of a chemical species depends in part on the length scale characterizing its vertical gradient. It can be shown (Brasseur & Solomon 1984) that the timescale appropriate to transport by vertical advection is given by

$$t_w = H/\bar{w}^*,$$

and that of diffusion is

$$t_\mathrm{d} = H^2/K_{zz},$$

where $H$ is the scale height of a chemical species, $\bar{w}^*$ is the mean vertical velocity, and $K_{zz}$ is the vertical diffusion coefficient. This arises because advection can only transport material in the direction of flow, whereas diffusion is expected to be isotropic. Thus the ratio of timescales for vertical diffusion and for vertical advection depends not only on the magnitudes of $K_{zz}$ and $\bar{w}^*$, but also on the vertical scale height of the species in question. Diffusion assumes greater importance for species with small vertical scale heights, such as water vapour and atomic oxygen, and lesser importance for those constituents whose vertical scale height is large (order of 10 km or more) such as carbon monoxide and nitric oxide.

Downloaded from rsta.royalsocietypublishing.org

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

## 4. Planetary waves

We have already mentioned that selective transmission of upward-propagating gravity waves by stratospheric planetary waves can have important effects on the distribution and variations of mesospheric turbulence. Stationary planetary waves can also propagate to the mesosphere during the winter season, as clearly revealed in the analysis of LIMS data by Dunkerton & DeLisi (1986). It is also interesting to note that longitude-dependent breaking of small-scale gravity waves may actually lead to the formation of planetary-scale disturbances within the winter mesosphere (Holton 1984). At mesospheric altitudes, planetary waves undergo relatively rapid thermal and mechanical dissipation, resulting in potentially important forcing of the mean circulation of the lower mesosphere and associated mean transport of chemical species as discussed above. From the viewpoint of transport of chemical species, perhaps the most important transport effect of planetary waves is that they distort the zonal flow field such that rapid local transport can occur in the meridional direction over planetary (order of thousands of kilometres) lengthscales. Any species with a substantial meridional gradient can therefore undergo important variations due to such displacements. If the wave dynamics remains approximately linear, then the transport will be reversible and hence only of brief and localized importance (i.e. the constituent field will be briefly distorted and rapidly returned to its original configuration). However, if significant nonlinearity occurs, then the large-scale distributions of chemical species can be affected irreversibly. In contrast to the previous discussion, therefore, we now consider briefly the role of meridional gradients in chemical species and their displacement by planetary scale waves.

Sporadic variations in electron densities are often observed in the mesosphere, a phenomenon known as the 'winter anomaly'. The electron densities within the mesosphere are produced by photoionization of nitric oxide (see Brasseur & Solomon 1984, and references therein), so that

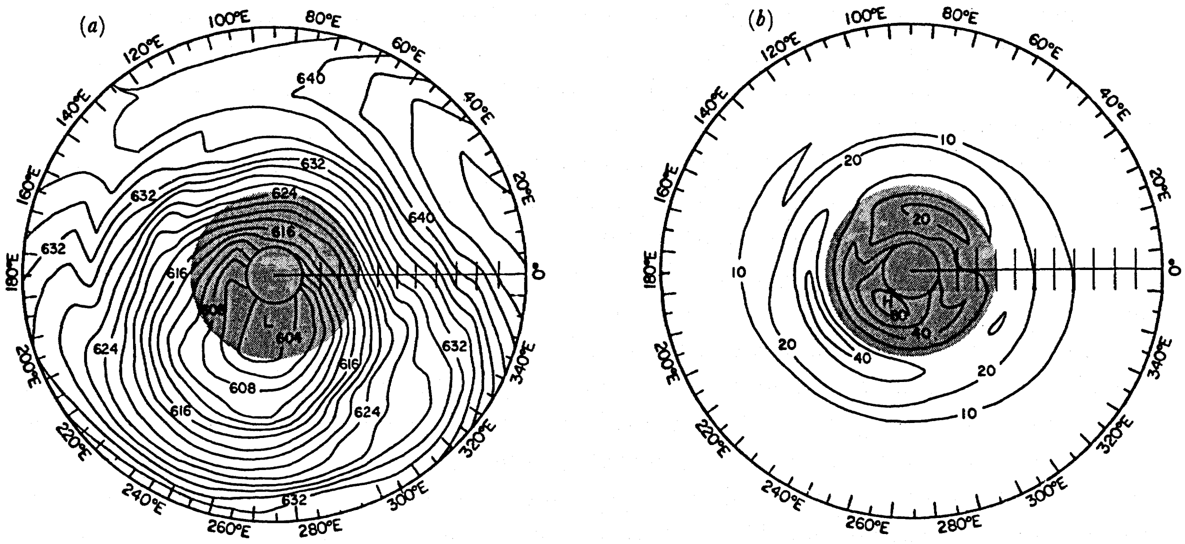

FIGURE 3. LIMS Northern Hemisphere geopotential height ($10^{-2}$ m) (*a*), and night-time $NO_2$ mixing ratio (parts per billion by volume; 1 billion represents $10^9$) fields (*b*) at 0.1 mbar. The height is for 7 January, 1979, and the $NO_2$ is an average over the period 5–9 January, 1979. Each tick mark on the Greenwich meridian represents 4° of latitude starting at 40° N. The shaded area indicates the polar-night region. (From Russell *et al.* (1984).) (1 mbar = $10^2$ Pa.)

Downloaded from rsta.royalsocietypublishing.org

variations in nitric oxide might be a candidate mechanism to explain this phenomenon. Because nitric oxide is not destroyed photochemically in the polar-night region, a large gradient in its distribution and photochemical lifetime exists across the polar-night terminator, and rapid meridional displacements associated with processes such as planetary waves can lead to large, local variations in nitric oxide and electron densities (Geller & Sechrist 1971; Manson 1971; Kawahira 1984; Garcia *et al.* 1987). Other factors such as temperature variations may also contribute to the winter anomaly. Satellite observations (Russell *et al.* 1984) of nitrogen dioxide have, however, revealed the importance of planetary-wave displacements in the lower mesosphere as illustrated in figure 3. Similarly, carbon monoxide is expected to exhibit large gradients near the polar-night region, and planetary-wave displacements may yield variations in its density in the lower mesosphere that are as large as a factor of one hundred near 55 km (Bevilacqua *et al.* 1985).

Other chemical species are likely to be influenced by planetary waves during winter. Clearly, planetary waves will be of greatest importance for those species with the largest gradients, probably nitric oxide and carbon monoxide, but water vapour and molecular hydrogen are also likely to exhibit significant variations in high latitude winter when planetary waves are present.

## 5. Tides

Thermal tides excited largely by ozone heating lead to substantial short-period variations in mesospheric temperatures and zonal winds. Chapman & Lindzen (1970) present a comprehensive review of tidal theory, whereas Forbes (1984) describes tidal models and their ability to simulate observations in detail. Tidal variations in temperature and zonal winds depend strongly on season and latitude in a manner not completely understood at present, but tidal fluctuations in temperature and zonal winds near the mesopause can be on the order of tens of kelvins and tens of metres per second, respectively.

Like planetary waves, the effect of tides is largely local and transient unless dissipation occurs, in which case tidal forcing can influence the mean circulation and long-term transport of chemical species. Lindzen (1981) shows that it is likely that tides do not break except above about 80 km in the tropics.

The large temperature perturbations associated with tides are likely to affect the temperature-dependent chemistry of the mesosphere in important ways. Forbes (1981) shows that the temperature-dependent ion chemistry of the mesosphere is strongly dependent upon tides. Petit-Didier & Teitlebaum (1977) have discussed the effect of tides on the green line airglow emission of atomic oxygen near the 100 km level. The oxygen and ozone chemistry of the mesosphere is expected to be particularly sensitive to tidal forcing.

Finally, it is interesting to note that a coupling may exist between tides and gravity waves. The turbulent diffusion generated by a breaking gravity wave depends on the background zonal wind speed at the breaking level; indeed, to a first approximation, the diffusion should vary as $(u-c)^4$, where $u$ is the zonal wind speed and $c$ the phase speed of the breaking wave, according to linear wave theory. Thus, tidal variations in zonal wind speed may have significant effects on the local, longitude (or time) dependent diffusion due to breaking gravity waves (Bjarnason *et al.* 1987). This can affect the diurnal variations of chemical species in the mesosphere. Conversely, the dissipation of tides is likely to vary with the background turbulence field (Forbes 1984).

Downloaded from rsta.royalsocietypublishing.org

## 6. CONCLUSIONS AND SOME OUTSTANDING PROBLEMS

The understanding of mesospheric transport processes has advanced greatly in recent years, through both observational and theoretical studies. In particular, the recognition of the important role of breaking gravity waves in mesospheric turbulent transport and in forcing the large-scale mean meridional circulation of the mesosphere has placed the theoretical framework of mesospheric dynamics on firmer ground than previously possible. The observations of turbulence by radar methods, and the satellite data on mesospheric ozone, provide important insight into these phenomena. Nevertheless, many important aspects of gravity-wave breaking remain only partly understood, in particular the nonlinear effects of wave breaking and the localization of turbulent transport (Fritts 1984; Fritts & Dunkerton 1985).

Other waves can produce both local and large-scale transport effects. Some effects of planetary, Kelvin, and tidal oscillations have been discussed here. The lack of global information on a long-lived mesospheric tracer makes it difficult to quantify the importance of such processes, but it is likely that planetary waves are responsible for significant transport in the winter mesosphere. Kelvin waves play an important role in the tropical semiannual oscillation near the mesopause (Dunkerton 1982) and the associated transport of chemical constituents (Gray & Pyle 1986).

A good deal of chemical-tracer data shows that the mean circulation of the mesosphere plays a significant role in establishing the seasonal and latitudinal variations in a number of chemical species such as carbon monoxide and nitric oxide. In spite of important ground-based and rocket studies, further understanding is impeded by a lack of global-satellite data. An understanding of the mesospheric mean meridional circulation also requires detailed knowledge of the radiative balance. Major uncertainties remain in the calculation of non-local thermodynamic equilibrium cooling rates at mesospheric altitudes (Dickinson 1984).

The National Center for Atmospheric Research is sponsored by the National Science Foundation.

## REFERENCES

Allen, M., Yung, Y. L. & Waters, J. W. 1981 Vertical transport and photochemistry in the terrestrial mesosphere and lower thermosphere (50–120 km). *J. geophys. Res.* **86**, 3617–3627.

Allen, M., Lunine, J. I. & Yung, Y. L. 1984 The vertical distribution of ozone in mesosphere and lower thermosphere. *J. geophys. Res.* **89**, 4841–4872.

Balsley, B. B., Eclund, W. L. & Fritts, D. C. 1983 VHF echoes from the high-latitude mesosphere and lower thermosphere: observations and interpretations. *J. atmos. Sci.* **40**, 2451–2466.

Bevilacqua, R. M., Olivero, J. J., Schwartz, P. R., Gibbins, C. J., Bologna, J. M. & Thacker, D. J. 1983 An observational study of water vapor in the mid-latitude mesosphere using ground-based microwave techniques. *J. geophys. Res.* **88**, 8523–8534.

Bevilacqua, R. M., Stark, A. A. & Schwartz, P. R 1985 The variability of carbon monoxide in the terrestrial mesosphere as determined from ground-based observations of the $J = 1 \rightarrow 0$ emission line. *J. geophys. Res.* **90**, 5777–5782.

Bjarnason, G. B., Solomon, S. & Garcia, R. R. 1987 Tidal influences on gravity wave breaking and diffusion. *J. geophys. Res.* **92**, 5609–5620.

Brasseur, G. & DeBaets, P. 1986 Ions in the mesosphere and lower thermosphere: a two-dimensional model. *J. geophys. Res.* **90**, 4025–4026.

Brasseur, G. & Solomon, S. 1984 *Aeronomy of the middle atmosphere.* Dordrecht, Holland: D. Reidel.

Chapman, S. & Lindzen, R. S. 1970 *Atmospheric tides.* New York: Gordon and Breach.

Downloaded from rsta.royalsocietypublishing.org

Chao, W. C. & Schoeberl, M. R. 1984 On the linear approximation of gravity wave saturation in the mesosphere. *J. atmos. Sci.* **41**, 1893–1898.

Clancy, R. T., Muhleman, D. O. & Berge, G. L. 1982 Microwave spectra of terrestrial mesospheric CO. *J. geophys. Res.* **87**, 5009–5014.

Clancy, R.T., Muhleman, D. O. & Allen, M. 1984 Seasonal variability of CO in the terrestrial mesosphere. *J. geophys. Res.* **89**, 9673–9676.

Dickinson, R. E. 1984 Infrared radiative cooling in the mesosphere and lower thermosphere. *J. atmos. terr. Phys.* **46**, 995–1008.

Dunkerton, T. J. 1978 On the mean meridional mass motions of the stratosphere and mesosphere. *J. atmos. Sci.* **35**, 2325–2333.

Dunkerton, T. J. 1982 Theory of the mesopause semiannual oscillation, *J. atmos. Sci.* **38**, 2681–2690.

Dunkerton, T. J. & Butchart, N. 1984 Propagation and selective transmission of internal gravity waves in a sudden warming. *J. atmos. Sci.* **41**, 1443–1460.

Dunkerton, T. J. & DeLisi, D. P. 1986 Evolution of potential vorticity in the winter stratosphere of January–February, 1979. *J. geophys. Res.* **91**, 1199–1208.

Elphinstone, R. D., Murphree, J. S. & Cogger, L. L. 1984 Dynamics of the lower thermosphere consistent with satellite observations of 5577 Å airglow. 2. Atomic oxygen, local turbulence and global circulation results. *Can. J. Phys.* **62**, 382–395.

Forbes, J. M. 1981 Tidal effects of D and E region ion chemistries. *J. geophys. Res.* **86**, 1551–1563.

Forbes, J. M. 1984 Middle atmosphere tides. *J. atmos. terr. Phys.* **46**, 1049–1067.

Frederick, J. E. & Orsini, N. 1982 The distribution and variability of mesospheric odd nitrogen: a theoretical investigation. *J. atmos. terr. Phys.* **44**, 479–488.

Fritts, D. C. 1984 Gravity wave saturation in the middle atmosphere: a review of theory and observations. *Rev. Geophys. Space Phys.* **22**, 275–308.

Fritts, D. C. & Dunkerton, T. J. 1985 Fluxes of heat and constituents due to convectively unstable gravity waves. *J. atmos. Sci.* **42**, 549–556.

Garcia, R. R. & Solomon, S. 1985 The effect of breaking gravity waves on the dynamics and chemical composition of the mesosphere and lower thermosphere. *J. geophys. Res.* **90**, 3850–3868.

Garcia, R. R., Solomon, S., Avery, S. K. & Reid, G. C. 1987 Transport of nitric oxide and the D-region winter anomaly. *J. geophys. Res.* **92**, 977–994.

Geller, M. A. & Sechrist, C. F. 1971 Coordinated rocket measurements of the D-region winter anomaly 2. Some implications. *J. atmos. terr. Phys.* **33**, 1027–1040.

Gray, L. J. & Pyle, J. A. 1986 Semi-annual oscillation and equatorial tracer distributions. *Q. Jl R. met. Soc.* **112**, 387–408.

Hays, P. B. & Olivero, J. J. 1970 Carbon dioxide and monoxide above the troposphere. *Planet. Space Sci.* **18**, 1729–1733.

Hines, C. O. 1970 Eddy diffusion coefficients due to instabilities in internal gravity waves. *J. geophys. Res.* **75**, 3937–3939.

Hodges, R. R. 1969 Eddy diffusion coefficients due to instabilities in internal gravity waves. *J. geophys. Res.* **74**, 4087–4090.

Holton, J. R. 1982 The role of gravity wave induced drag and diffusion in the momentum budget of the mesosphere. *J. atmos. Sci.* **39**, 791–799.

Holton, J. R. 1983 The influence of gravity wave breaking on the general circulation of the middle atmosphere. *J. atmos. Sci.* **40**, 2497–2507.

Holton, J. R. 1984 The generation of mesospheric planetary waves by zonally asymmetric gravity wave breaking. *J. atmos. Sci.* **41**, 3427–3430.

Holton, J. R. & Wehrbein, W. M. 1980 A numerical model of the zonal mean circulation of the middle atmosphere. *Pure appl. Geophys.* **118**, 284–306.

Horvath, J. J., Frederick, J. E., Orsini, N. & Douglass, A. R. 1983 Nitric oxide in the upper stratosphere: measurements and geophysical interpretation. *J. geophys. Res.* **88**, 10809–10817.

Houghton, J. T. 1978 The stratosphere and mesosphere. *Q. Jl R. met. Soc.* **104**, 1–29.

Jones, W. L. & Houghton, J. T. 1972 The self-destructing internal gravity wave. *J. atmos. Sci.* **29**, 844–849.

Kasting, J. F. & Roble, R. G. 1981 A zonally averaged chemical-dynamical model of the lower thermosphere. *J. geophys. Res.* **86**, 9641–9653.

Kawahira, K. 1984 Dynamical influences of planetary waves on nitric oxide variations in the D-region. *J. atmos. terr. Phys.* **46**, 321–333.

Leovy, C. 1964 Simple models of thermally driven mesospheric circulation. *J. atmos. Sci.* **21**, 327–341.

LeTexier, H., Solomon S. & Garcia, R. R. 1987 Seasonal variability of the OH Meinel bands. *Planet. Space Sci.* (In the press.)

Lindzen, R. S. 1971 Tides and gravity waves in the upper atmosphere. In *Mesospheric models and related experiments* (ed. G. Fiocco), pp. 122–130. Hingham, Massachusetts: D. Reidel.

Lindzen, R. S. 1981 Turbulence and stress owing to gravity wave and tidal breakdown. *J. geophys. Res.* **86**, 9707–9714.

Downloaded from rsta.royalsocietypublishing.org

Manson, A. H. 1971 The concentration and transport of minor constituents in the mesosphere and lower thermosphere (70–110 km) during periods of anomalous absorption. *J. atmos. terr. Phys.* **33**, 715–721.

Matsuno, T. 1982 A quasi one-dimensional model of the middle atmosphere circulation interacting with internal gravity waves. *J. met. Soc. Japan* **60**, 215–226.

Murgatroyd, R. J. & Singleton, F. 1961 Possible meridional circulations in the stratosphere and mesophere. *Q. Jl R. met. Soc.* **87**, 125–135.

Murphy, A. K. 1985 Satellite measurements of atmospheric trace gases. D. Phil. thesis, Oxford University.

Petit-Didier, M. & Teitlebaum, H. 1977 Lower thermospheric emissions and tides. *Planet. Space. Sci.* **25**, 711–721.

Russell, J. M., Solomon, S., Gordley, L. L., Remsberg, E. E. & Callis, L. B. 1984 The variability of stratosphere and mesospheric $NO_2$ in the polar winter night observed by LIMS. *J. geophys. Res.* **89**, 7267–7275.

Schoeberl, M. R. & Strobel, D. F. 1978 The zonally averaged circulation of the middle atmosphere. *J. atmos. Sci.* **35**, 577–591.

Schoeberl, M. R. & Strobel, D. F. 1984 Nonzonal gravity wave breaking in the winter mesosphere. In *Dynamics of the middle atmosphere* (ed. J. R. Holton & T. Matsuno), pp. 45–64. Dordrecht, Holland: D. Reidel.

Schoeberl, M. R., Strobel, D. F. & Apruzese, J. P. 1983 A numerical model of gravity wave breaking and stress in the mesosphere. *J. geophys. Res.* **88**, 5229–5239.

Solomon, S., Crutzen, P. J. & Roble, R. G. 1982 Photochemical coupling between the thermosphere and the lower atmosphere 1. Odd nitrogen from 50 to 120 km. *J. geophys. Res.* **87**, 7206–7220.

Solomon, S., Garcia, R. R., Olivero, J. J., Bevilacqua, R. M., Schwartz, P. R., Clancy, R. T. & Muhleman, D. O. 1985 Photochemistry and transport of carbon monoxide in the middle atmosphere. *J. atmos. Sci.* **42**, 1072–1083.

Swider, W. 1978 Daytime nitric oxide at the base of the thermosphere. *J. geophys. Res.* **83**, 4407–4410.

Thomas, R. J., Barth, C. A. & Solomon, S. 1984 Seasonal variations of ozone in the upper mesosphere and gravity waves. *Geophys. Res. Lett.* **11**, 673–676.

Vincent, R. A. & Reid, I. M. 1983 HF doppler measurements of mesospheric gravity wave momentum fluxes. *J. atmos. Sci.* **40**, 1321–1332.

## *Discussion*

M. E. McIntyre (*Department of Applied Mathematics and Theoretical Physics, University of Cambridge, U.K.*). It is very impressive how vertical mixing attributable to breaking gravity waves seems to be the only physically plausible transport process that can explain certain observed photochemical phenomena in the mesosphere, such as the seasonal variability of the 557.7 nm airglow. It all means that we must think seriously about how efficient this vertical mixing process might really be.

Chao, Schoeberl, Fritts and Dunkerton have recently pointed out that the 'turbulent Prandtl number' probably depends sensitively upon the degree of supersaturation of the breaking wave, that is to say the amount by which the amplitude of the wave locally exceeds the amplitude for incipient breaking. Their argument applies only to the vertical mixing of potential temperature, and it remains to be clarified *inter alia* whether the same will apply to dynamically passive tracers; but the possible implications for mesospheric modelling still need to be taken note of. If their results correctly reflect reality, we must expect a much steeper increase in vertical diffusivities with height than the height dependence of the gravity-wave spectrum itself might suggest. This is because of the fact that the vertical wavelengths of breaking gravity waves increase with height, and in the mesosphere become comparable to $2\pi$ times the density scale height. The turbulent Prandtl number tends to increase with the degree of supersaturation; and the degree of supersaturation can be expected to increase as the wave-breaking process becomes more 'sudden', like a steeply sloping as opposed to a shallowly sloping ocean beach.

These considerations might also force some revision of the standard ideas about deducing vertical diffusivities from observed turbulent intensities (see my comment on Dr Röttger's

Downloaded from rsta.royalsocietypublishing.org

paper). Some laboratory experiments that should bear on these questions are being planned by Dr P. F. Linden at Cambridge.

### *References*

Chao, W. C. & Schoerberl, M. R. 1984 *J. atmos. Sci.* **41**, 1893–1898.
Fritts, D. C. & Dunkerton, T. J. 1985 *J. atmos. Sci.* **42**, 549–556.

Susan Solomon. I agree that the question of gravity-wave saturation is critical to the evaluation of the turbulent transport associated with breaking gravity waves. A number of chemical tracers exist that can provide important observational tests for such ideas, such as water vapour. Observations of water vapour by Bevilacqua and colleagues suggests that the turbulent diffusion near 80 km may be considerably smaller than previously thought, perhaps because of the processes that Dr McIntyre has indicated.