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COMPOSITION CHANGES IN THE LOWER THERMOSPHERE

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Abstract

The upper atmosphere over the winter polar region remains about as warm as that at low latitudes. The most likely heat source in the thermosphere and mesosphere to maintain this warmth is thought to be subsidence, and its rate can be estimated by equating the compressional heating to the normal rate of solar heat input at low latitudes. The average rate of inflow into the polar region required to produce this subsidence can also be calculated. Further, just above the turbopause, the inflow of different constituents is proportional to the product of the concentration and the scale height, whereas the loss by motion downward is proportional to the concentration but independent of the scale height; this effect leads to a concentration of the lighter constituents in the thermosphere over the winter polar region. This is observable in terms of the helium bulge over the winter polar region, and it should also lead to an increase in oxygen concentration. These effects may be enhanced when there is a sudden breakdown of the polar vortex.

Important changes in the composition of the upper atmosphere can be brought about by large scale circulation near the turbopause. The most important circulation is probably the one that maintains the warmth of the upper atmosphere over the winter polar region. This circulation is probably essentially meridional in character, producing inflow toward the winter polar region and downward motion and compressional heating of the upper atmosphere. The magnitude of the downward motion can be estimated by equating the compressional heating to the solar heating that occurs at lower latitudes; this is justified to the degree that compressional heating is the principal heat source over the winter polar region and that the upper atmosphere is about as warm over the winter polar region as at lower latitudes. The procedure is not justified at altitudes where quasi-horizontal eddies provide an important heat transfer from low latitudes to high; however, at the altitudes of concern here, the heat capacity of the atmosphere and the observed wind pattern indicate that such eddies do not provide the principal heat transport. The recombination of atomic oxygen also constitutes a heat source (Johnson, 1958), and this must be taken into account, especially over the winter polar region where the effect may be enhanced by the downward motion of the atmosphere (Kellogg, 1961).

The rate of heat release per unit mass as a result of compressional heating associated with downward motion or subsidence is

$$\frac{dh}{dt} = C_p \, V_v \frac{dT}{dz} + V_v g$$

where C_p is the specific heat at constant pressure, V_v is the vertical velocity (positive upward), g is the acceleration of gravity, and dT/dz is the temperature gradient, which is assumed to remain constant as the vertical motion proceeds. This can be equated to the heat input by absorption of solar energy that occurs at lower latitudes, on the basis that the subsidence heating over the winter polar region must approximate the solar input at lower latitudes, otherwise the winter polar region would be markedly colder than it is observed to be.

Figure 1 shows an estimate of the equinoctial heat input above various altitudes in the atmosphere at 30° latitude. The heat inputs due to absorption of solar ultraviolet radiation by O_2 and O_3 are shown, as well as the chemical heat released by the recombination of atomic oxygen. The infrared contributions, as calculated by Kondratiev et al. (1966), are also shown; where the infrared provides a net loss above the altitude in question, it is labeled -IR, and where it provides a net gain, +IR. Note that the atomic oxygen heating near 80 km is the greatest single energy input into the atmosphere. Over the winter polar region, its contribution is probably such as to significantly reduce the vertical velocity required to maintain the warmth of the upper atmosphere.

Figure 2 shows the vertical velocities required to produce the compressional heating equivalent to solar heating at low latitude. Twice the low latitude rate of oxygen recombination has been used in the calculation of the vertical velocities shown in Figure 1 to allow for the effect of the circulation on the atomic oxygen supply. The relatively rapid rate of heat release by oxygen recombination is responsible for the bulge in the vertical velocity curve near 80 km; it produces no perceptible effect above 90 km and below 65 km. Also shown in Figure 2 are the average meridional horizontal velocities required near 60° latitude in order to maintain the required vertical velocities over the polar region.

Such a circulation pattern can produce important changes in atmospheric composition as a result of the different vertical distributions of atmospheric constituents in the diffusosphere. The inflow to the polar region of different atmospheric gases above the turbopause is proportional to the product of the meridional velocity, the concentration, and the scale height; because of the scale height factor, the inflow is enriched in the lighter atmospheric constituents by comparison with the heavier. The downward flow removes the different atmospheric gases in proportion to the product of the vertical velocity and the concentration. As a result, the lighter gases tend to accumulate and build up in concentration in a region of inflow. The biggest effect occurs with helium, which has a scale height about seven times larger than the average scale height; in the absence of other effects, the helium concentration could continue to build up until its relative concentration increased by a factor of seven, at which point the downward losses would match the inflow. However, the increased helium abundances are attenuated by other factors, the most important of which is outflow through the exosphere. It is possible to estimate from calculations of McAfee (1967) that a vertical upward flow of about 4×10^8 atoms $cm^{-2}\ s^{-1}$ is required to support an increase of 50% in helium concentration in a portion of the exosphere. The inflow of helium into the polar region can be estimated as follows. The vertical downward current at the turbopause, from Figure 2, is about 10 cm s^{-1}, and the total downward flux of atmospheric particles there is therefore about 5×10^{13} molecules $cm^{-2}\ s^{-1}$. Without any enhancement of the helium concentration, the downward flux of helium would be about 2.5×10^8 atoms $cm^{-2}\ s^{-1}$, and the total inflow corresponds to an amount seven times larger than this. Therefore, the excess flux amounts to about 15×10^8 atoms $cm^{-2}\ s^{-1}$. The helium concentration might therefore build up by about a factor of two, in which case the downward losses would be 5.0×10^8 atoms

$cm^{-2}\ s^{-1}$ and the upward losses 12.5×10^8 atoms $cm^{-2}\ s^{-1}$ -- approximately sufficient to compensate for the outflow through the exosphere.

An increase of helium over the winter polar region has been deduced by Keating and Prior (1967), based on observations of satellite orbital decay. They find a difference between the winter and summer poles amounting to a factor between 2.5 and 4.4. There is probably an inverse effect over the summer pole acting to decrease the helium concentrations there, so the circulation mechanism can probably explain a factor near 4 for the ratio of the helium concentrations over the summer and winter poles.

It is reasonable to inquire whether a similar effect occurs on a diurnal basis near the temperature maximum and minimum in the thermosphere. The heat capacity of the atmosphere near the turbopause is great enough so that diurnal changes there are expected to be small, and hence circulations probably do not develop to compensate for the lack of solar heating on such a short time scale. Hence, such an effect should not be expected.

The polar circulation patterns should also affect the atomic oxygen concentrations, though not so strongly, since the molecular weight difference relative to the average is not so great in this case. However, the effect is probably large enough to affect the ionospheric chemistry in a noticeable degree - for example, by creating the F region winter anomaly.

There is probably enhanced inflow and subsidence over the winter polar region when there is a breakdown in the polar vortex. Therefore enhanced effects on the helium and oxygen build ups should be expected at that time. This might be looked in ionospheric perturbations for the oxygen effect or in satellite orbital decay with suitable orbit parameters for the helium effect.

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FIGURE CAPTIONS

Figure 1. Heat input above various altitudes, based on absorption of solar ultraviolet radiation by O_2 and O_3, and on energy released in the oxygen recombination processes $O + O$. Also shown is the energy loss (-IR) and energy gain (+IR) due to infrared radiation, mainly by CO_2. The curve applies for 30° latitude at the equinox.

Figure 2. Vertical and horizontal velocities required to provide a heat source over the winter polar region equivalent to the solar heat source at low latitude, based on data from Figure 1.

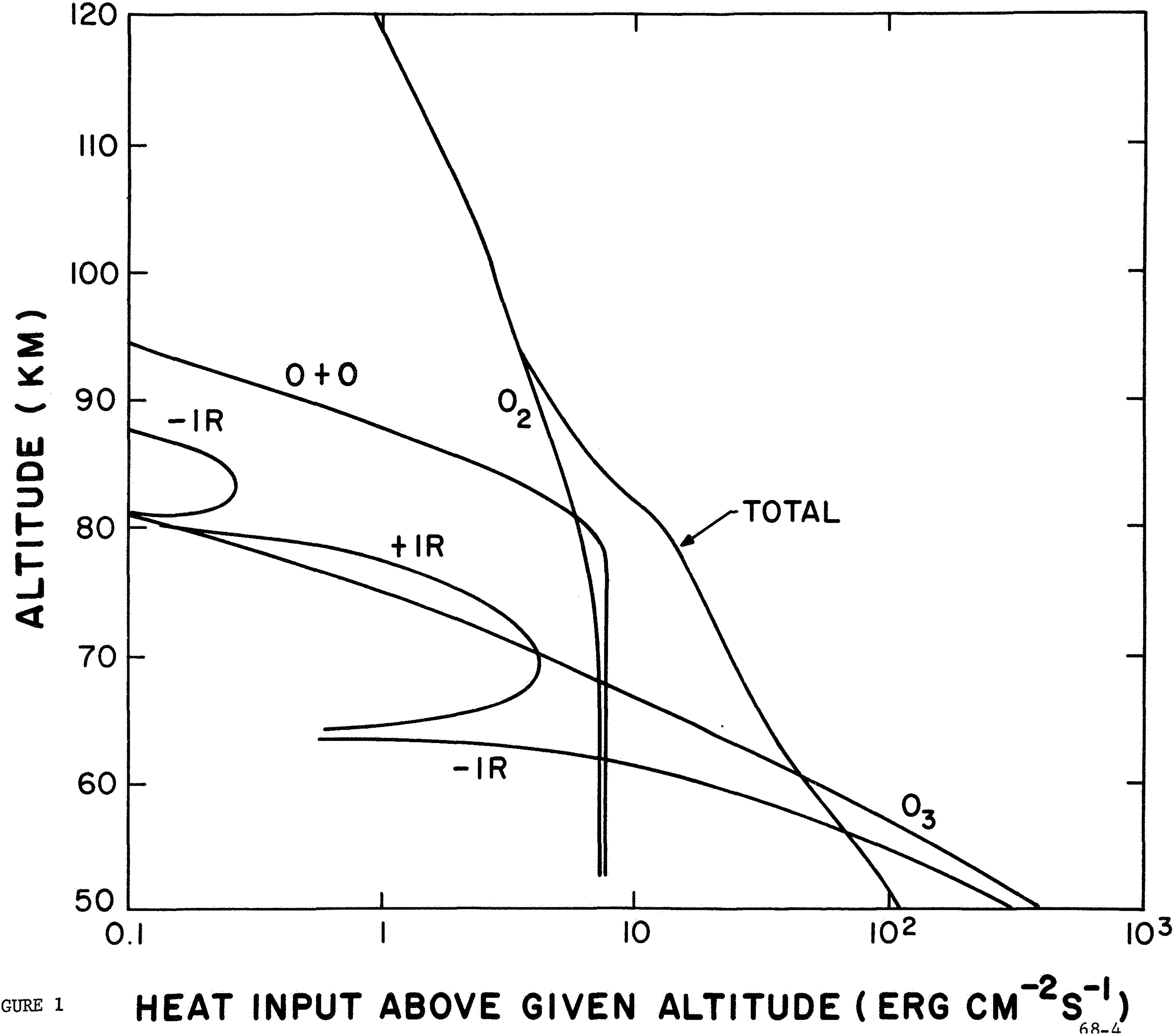
ALTITUDE (KM)
120
110
100
90
80
70
60
50
0.1
1
10
10^2
10^3
HEAT INPUT ABOVE GIVEN ALTITUDE (ERG CM^{-2}S^{-1})
O+O
-IR
+IR
-IR
O_2
O_3
TOTAL

FIGURE 1

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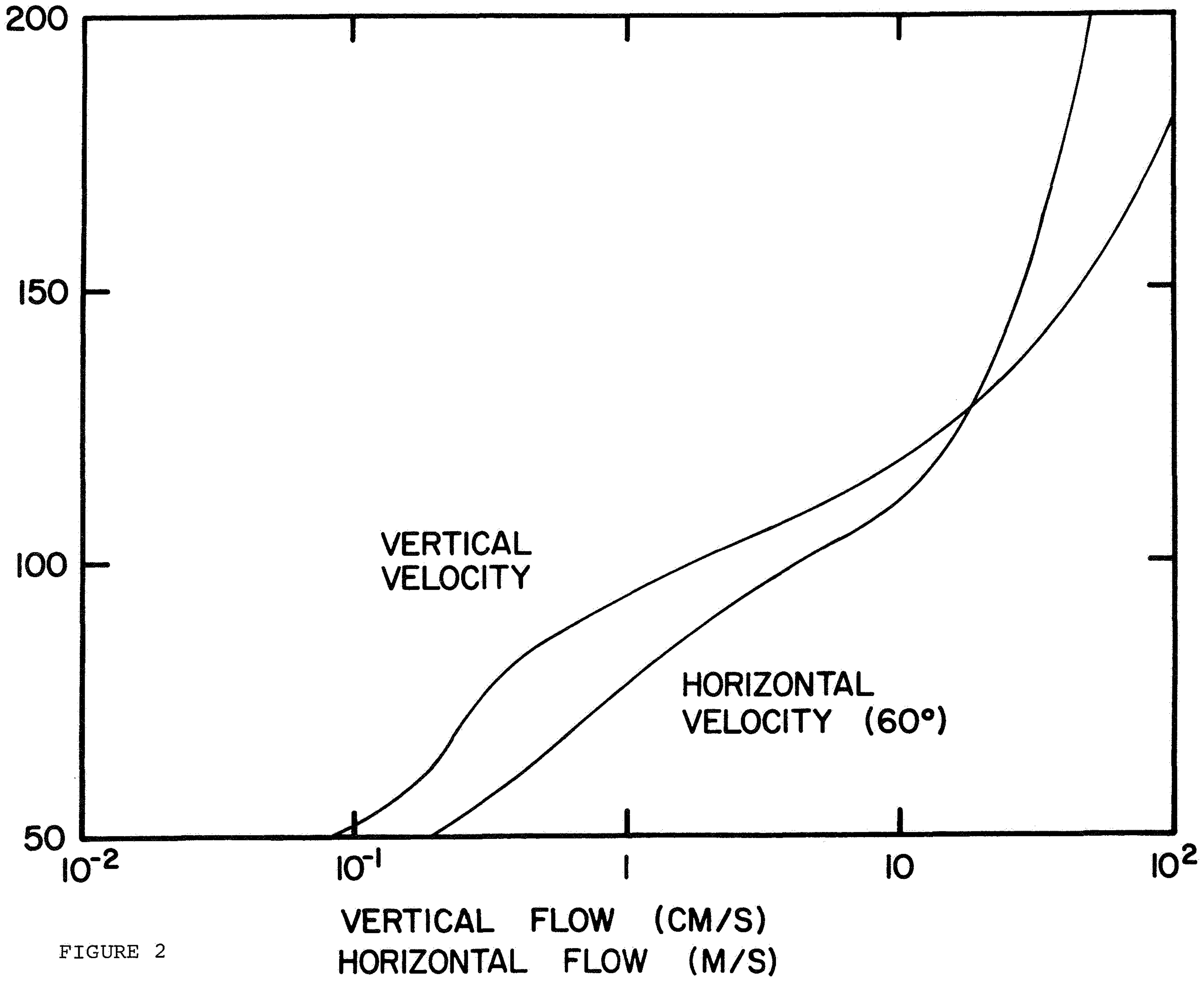
200
150
100
50
10^-2
10^-1
1
10
10^2
VERTICAL VELOCITY
HORIZONTAL VELOCITY (60°)
VERTICAL FLOW (CM/S)
HORIZONTAL FLOW (M/S)

FIGURE 2