NOTES AND CORRESPONDENCE

**A Possible Influence of Sea Surface Temperature Variation
on the Recent Development of Ozone Hole****By Kunihiko Kodera and Koji Yamazaki***Meteorological Research Institute, Nagamine, Tsukuba, Ibaraki 305, Japan
(Manuscript received 23 February 1989, in revised form 12 April 1989)***Abstract**

A possible cause of the recent decrease of planetary wave activity and Antarctic ozone depletion in spring is proposed. The tropospheric stationary wave structure in the southern hemisphere shows substantial variation during 1979 to 1988. Before the 1980's, especially in 1979, a well-developed tropospheric ridge was situated in the South Pacific and the stationary wave propagated into the stratosphere, while after 1985 the tropospheric ridge became weaker and split into two ridges, and no vertical propagation was clearly seen. In 1988, however, the vertically propagating wave number 1 structure was recovered. This change of planetary wave structure in the South Pacific seems to be related to the sea surface temperature anomaly in the low latitude South Pacific. A possible role of the sea surface temperature variation in the recent development of the ozone hole is also discussed.

1. Introduction

Farman *et al.* (1985) showed spectacular decrease in October Antarctic total ozone starting at the end of 1970's. They associated this quasi-monotonous decreasing of ozone with the influence of increasing man-made halocarbons. Since a large concentration of chlorine monoxide (ClO) at low altitudes of the spring stratosphere over Antarctica was detected (Barrett *et al.*, 1988), the primary importance of a chemical mechanism for the development of the ozone hole has become widely accepted.

In 1988, however, one year after the deepest Antarctic ozone depletion (Krueger *et al.*, 1988), TOMS data showed a great recovery from the deepening ozone hole. The weakening of the ozone hole in 1988 is related to the fact that the polar vortex was broken up very early at the end of October (Schoeberl, 1988).

The possibility of the influence of planetary wave activity on the interannual variation of the ozone hole has been pointed out by Mahlman and Fels (1986) and a large decrease of lower stratospheric planetary wave activity since 1979 until 1987 was reported (Nagatani and Miller, 1987; Newman and Randel, 1988). The cause of the decrease, however, has not been explored.

In the present study, first we examine the interannual variation of the planetary wave structure from 1979 to 1988 in the troposphere and stratosphere. Next, sea surface temperature (SST) variation is discussed as a possible cause of the interannual variation of tropospheric planetary waves, and finally a possible relationship between the recent ozone decrease and SST variation is briefly discussed.

2. Evolution of a stationary wave structure

In the present section, interannual changes of the horizontal and vertical structure of planetary waves in the troposphere as well as in the stratosphere are examined using the National Meteorological Center (NMC) and the Japan Meteorological Agency (JMA) monthly mean geopotential data over the period from 1979 to 1988.

To see the planetary wave structure, latitude-longitude section of zonally asymmetric component of geopotential height is juxtaposed according to pressure levels. This may be primitive but is straightforward to trace the three-dimensional propagation of planetary waves, especially near their source regions.

Fig. 1 shows the October mean zonally asymmetric component of geopotential height in the southern hemisphere from 30°S to 90°S, at 50, 100, 200, and 500 mb levels. Fig. 1a is for 1979, 1980 and 1981,

Fig. 1a. October mean zonally asymmetric component of NMC geopotential height, at 50, 100, 200 and 500 mb (from top to bottom) for 30–90°S, 0–360°E for 1979,1980 and 1981 (from left to right), respectively. Contour interval is 50 g.p.m. and negative values are shaded.

Fig. 1b. Same as in Fig. 1a , except for 1985, 1986 and 1987 (from left to right).

Fig. 2. Same as in Fig. 1, except for JMA geopotential height in October 1987 (left) and 1988 (right).

from left to right, respectively. Fig. 1b is the same as in Fig. 1a but for 1985, 1986 and 1987. (1982–1984 are not shown).
In the case of 1979 (Fig. 1a left), a well-developed stationary zonal wave number 1 structure is found

throughout the troposphere and stratosphere. A tropospheric ridge west of Chile can be traced to a stratospheric ridge south of New Zealand and Australia at 50 mb. This westward tilt of phase with increasing altitude is the characteristic of vertical

Fig. 3. Linear trend maps (30° – 90° S, 0° – 360° E) of mean October zonally asymmetric component of NMC geopotential height over 1979–1987 at 50, 100, 200 and 500 mb level (from top to bottom). Contours are every 5 g.p.m./year and negative values are shaded.

propagation of forced planetary waves. Although the tropospheric ridge is much weaker, planetary wave propagation from the troposphere into the stratosphere is still seen until 1982. After 1983, especially after 1985 (Fig. 1b), although the wave number 1 pattern is seen at the 50 mb level, there is no clear wave number 1 structure in the troposphere, where the ridge is split in two. Note also that the meridional extent of ridges is smaller after 1985. A tropospheric ridge south of New Zealand is traceable up to the stratosphere with no tilt of phase, showing that no apparent propagation of stationary waves from the troposphere occurred.

In the above discussion, we have examined long-term variation from 1979 to 1987 using NMC data. Our analyses are extended to 1988 using JMA data. Fig. 2 shows zonally asymmetric components of the

October mean geopotential height maps of JMA data in 1987 (left) and in 1988 (right). The zonally asymmetric component of the 1987 October mean geopotential height of JMA analysis (Fig. 2 left) is very similar to that of NMC analysis (Fig. 1b right); the tropospheric ridge is completely split in two. In October 1988 (Fig. 2 right), the tropospheric ridge recovered the early 1980's wave structure; the ridge is situated to the west of Chile and propagates upward and westward.

These examples demonstrate that the vertical propagation is well related to the horizontal structure in the troposphere. When the tropospheric wave is a clear wave number 1 structure with a developed ridge west of Chile, vertical propagation is clear, while the vertical propagation is not clear when ridge is split in two.

Fig. 4. Time series of October mean of a) total ozone at Syowa station in Antarctica ($69^{\circ}00'S$, $39^{\circ}35'E$), b) 100 mb south polar temperature averaged over 60° – $90^{\circ}S$, c) northward stationary eddy heat flux at 200 mb averaged over 40° – $70^{\circ}S$ and d) zonally asymmetric component of geopotential height at 500 mb in South Pacific averaged over the domain of 30° – $60^{\circ}S$ and 110° – $130^{\circ}W$. For b), c), and d) solid lines (1979–1987) are NMC data and dashed lines (1987–1988) are JMA data.

Fig. 5. Time series of October mean a) total ozone at Syowa station, b) zonally asymmetric component of 500 mb geopotential height in the South Pacific (same as in Fig. 4d), and of c) September–October mean sea surface temperature in the South Pacific averaged over the domain indicated by a close rhomboid in the Fig. 7. SST data are NOAA data from 1979 to 1984 and JMA data from 1985 to 1988.

3. Long-term variation of geopotential heights

Fig. 3 shows the results of trend analysis over 1979–1987 for zonally asymmetric component of the October NMC geopotential height at the 50, 100, 200 and 500 mb levels, from top to bottom, respectively.

At 500 mb level (Fig. 3, bottom), as was expected from the difference between 1979 and 1987 (Fig. 1), a large negative trend is found in the South Pacific west of Chile, and a positive trend south of South America and south of New Zealand. This negative trend continues to the 50 mb level, shifting westward. The trend in September is similar to that in October.

Fig. 4d shows time series of the October mean zonally asymmetric component of 500 mb geopotential height in South Pacific to the west of Chile (averaged over the domain 30° – $60^{\circ}S$ and 110° – $130^{\circ}W$). As expected from trend analysis (Fig. 3), the geopotential height decreases rather monotonically from 1979 until 1986 or 1987, while a large increase occurs in 1988. On the same figure (a) total ozone at Syowa station in Antarctica, (b) October mean 100

Fig. 6. Linear trend of September-October mean sea surface temperature during the period from 1974 to 1987. Unit is 0.01K/year. Contour interval is 0.04K/year. Negative(cooling trend) values are stippled.

Fig. 7. 15 year mean(1970-1984) sea surface temperature (SST) for September. Contour interval is 1°C. Stippled region denotes SST anomaly region used in the GCM experiment. A close rhomboid indicate the region representing the SST in the Fig. 5.

mb south polar temperature (averaged over 60°-90°S) and (c) October mean 200 mb poleward stationary eddy heat flux averaged over 40°-70°S, are also presented. These three variables show quite similar variation as the 500 mb geopotential height (curve d). Note that the poleward eddy heat flux is a good indicator of vertical propagation of planetary waves. The present results suggest that the October temperature and the ozone variation in the Antarctic stratosphere are related to the vertical propagation of planetary waves from the troposphere.

4. SST anomaly

In this section we consider a possible cause of the long-term geopotential height variation in the South Pacific. It is generally accepted that the lower latitude sea surface temperature (SST) anomaly has a large influence on mid-latitude tropospheric circulations (*e.g.* Blackmon *et al.*, 1983).

Fig. 6 shows the linear trend of September-October mean SST over the period from 1974 to 1987. An important increasing trend is seen in the

lower latitude South Pacific SST. Fig. 5 shows the time series of SST in the South Pacific averaged over the domain indicated by a close rhomboid in Fig. 7 (bottom), and the 500 mb geopotential height anomaly to the west of Chile of Fig. 4d (middle). A negative correlation is seen between the two curves (correlation coefficient over 1979 to 1988 is -0.73). This coherent increasing of SST in the South Pacific may be a cause of the variation of geopotential height in the South Pacific.

Unfortunately available data are very limited to study the causal relationship between the SST variation and the tropospheric planetary wave structure. In this respect a numerical experiment is performed with use of the tropospheric MRI General Circulation Model (GCM), which uses the modified Arakawa-Schubert cumulus parameterization (Tokio *et al.*, 1988).

From the same atmospheric initial condition on September 1, two integrations are made through the October. In run C, SST anomalies of -1°C (-2°C) are imposed over the lightly(heavily) stippled region

Fig. 8. October mean zonally asymmetric component of geopotential height at 500 mb for C run, W run and W-C (from top to bottom). Contour interval is 30 g.p.m for upper two panels and 10 g.p.m for the difference. Negative values are stippled.

in Fig. 7. In run W, anomalies of $+1^{\circ}\text{C}$ and $+2^{\circ}\text{C}$ are imposed. The climatological SST used is the 15 year mean (1970–1984) data. Note that the region is near the South Pacific Convergence Zone and the climatological SST over the region is the warmest at the same latitude.

The results show that precipitation over the SST anomaly region is enhanced in run W compared with that in run C. The maximum value of precipitation difference is about 5 mm/day at 130°W , 18°S . The October mean zonally asymmetric components of

geopotential height at 500 mb are shown in Fig. 8 for run C, run W and their difference. In run C, a wave number 1 structure is dominant at about 60°S and it is similar to that in 1979. In run W, the wave number 1 structure is split in two. The decrease of geopotential height to the west of Chile and the splitting of tropospheric ridge is simulated as expected. The experiment, however, is only one integration for each case, hence further study is needed to confirm the results.

Fig. 9. A possible mechanism for the influence of sea surface temperature variation on the stratospheric ozone content.

5. Summary and discussion

The results obtained in the present studies are:

- A substantial change of planetary wave structure in the troposphere occurs in the South Pacific region after 1979. A clear wave 1 structure in 1979 disappears completely after 1985 (Fig. 1). In 1988, however, the wave 1 structure is recovered (Fig. 2).
- Vertical propagation of planetary waves is related to the tropospheric wave structure. No clear propagation is found when the geopotential height to the west of Chile is lower and the tropospheric ridge is split in two.
- The 200 mb poleward stationary eddy flux, the 100 mb polar temperature and the total ozone at Syowa station show a long-term variation similar to the 500 mb geopotential anomaly in the South Pacific to the west of Chile (Fig. 4).
- The September-October mean SST in the low latitude South Pacific has a negative correlation with the mid-latitude 500 mb geopotential height anomaly in the South Pacific to the west of Chile (Fig. 5).
- The results of the numerical experiment show that the warming of lower latitude South Pacific SST can produce the depletion of the 500 mb geopotential height to the west of Chile.

In the Fig. 5, the October total ozone at Syowa station (top) is plotted with the lower latitude South Pacific SST (bottom). Except for a short-term variation, good correspondence between the SST and the ozone variation is clearly seen on the figure: the SST starts to increase from the end of 1970's, while ozone decreases from the same epoch. The correlation coefficient between the September-October mean SST and the total ozone at Syowa is -0.53 in October and -0.69 in November for the period from 1970 to 1988 (1973 missing).

From these results we may speculate a possible relationship between SST and ozone as follows (Fig. 9);

Anomalies in SST modulate heat sources and change the horizontal and vertical structure of planetary waves. The variation of wave activity in the stratosphere influences heat and ozone transport. As a consequence, the temperature field and ozone content change. The change of stratospheric temperature also affects ozone through chemical processes, especially through the formation of polar stratospheric clouds which are crucial for the heterogeneous reaction involved in a proposed mechanism of ozone destruction by halocarbons (*e.g.* Solomon *et al.*, 1986).

We do not consider the results of the present study as "conclusive evidence" of SST control of ozone, but a "working hypothesis" which is helpful for further study of the very complex phenomenon of the ozone hole. Chemical mechanisms alone cannot explain the whole aspect of ozone variation such as the quasi-biennial variation related to the equatorial zonal wind direction in the stratosphere (Garcia and Solomon, 1987), or 1988's increase associated with enhanced planetary wave activity. It is necessary to consider both the chemical and the dynamical influence as well (Fig. 9).

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近年のオゾンホールの発達に及ぼす海面水温の影響の可能性

小寺邦彦・山崎孝治

(気象研究所・気候研究部)

近年の南極域の春先のプラネタリー波の活動度の低下、及びオゾンの減少の原因についての考察を行った。1979年から1988年の間に、南半球の対流圏プラネタリー波の構造に大きな変化があることが見いだされた。この構造の変化には南太平洋低緯度の海面水温の変動が関連している可能性がある。こうした海面水温の変動が近年のオゾンホールの発達にどのような役割をはたしうるかについて議論した。