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HOW GRAVITY WAVES AFFECT FORMATION OF LOW TEMPERATURE REGION IN ANTARCTIC LOWER STRATOSPHERE

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Abstract: A mechanism is proposed for the formation of an "ozone hole" over Antarctica. Gravity waves emitted from the circum-continental mountain (or cliff) belt may be partly saturated in the lower stratosphere and suppress planetary wave activity there. This process results in shielding a poleward heat transport associated with planetary waves. A long-term trend of gravity wave activity and prevailing wind system for the past several years should be detected in the polar region.

1. Introduction

"Ozone hole" over Antarctica has been one of the most dramatic events recently found in the atmosphere. Among the various mechanisms of the "ozone hole" formation so far proposed, some of them are based on the atmospheric chemistry and a few are based on the simple atmospheric dynamics (TUNG *et al.*, 1986; TUNG, 1986; MAHLMAN and FELS, 1986), although the theoretical perspective is not clear. The only thing that is absolutely certain at the present stage is a very high correlation between the temperature structure in the Antarctic lower stratosphere and the ozone amount. Therefore, how and why very low temperatures lower than $-80°C$ are induced and maintained in the lower stratosphere over Antarctica throughout late spring, particularly in the past several years, is the most important target to be urgently attacked based on the atmospheric dynamics.

2. Possible Dynamical Causes

Several answers can be easily ready for the above question if we assume that the occurrence of such very low temperatures is exclusively associated with dynamical effects: (i) Planetary wave activity has waned year after year by some unknown causes (for example, depletion of hemispheric scale baroclinicity due to a rise of sea surface temperature around Antarctica), and has reached below a threshold level reducing the poleward heat transport. (ii) Some mechanism has newly appeared over and around Antarctica, which suppresses further heat transports associated with planetary waves toward the pole center. (iii) Both of (i) and (ii). Cause (i) is promising and should be clarified. Here, instead of (i), we propose mechanism (ii) which is deeply related with a potentially important effect of orographic gravity waves emitted from the circum-continental mountain (or cliff) belt. Gravity waves may be the most effective carrier which radiates surface stresses upward.

3. Gravity Wave Effects

Atmospheric gravity waves are generated when the wind blows over mesoscale mountains or cliffs. Generation of gravity wave stresses depends on variance of the mesoscale mountain height and surface wind velocity (PALMER *et al.*, 1987; TANAKA *et al.*, 1987). The variances are extremely large, mostly exceeding 0.3×10^6 m^2 over the circum-continental mountain (or cliff) area. A GCM simulation including gravity wave effects (see TANAKA *et al.*, 1987) showed that the zonally averaged gravity wave stress reaches about 1.5 Pa at latitudes over the circum-continental mountains (or cliffs) in the summer season, which is even larger than the maximum value in the northern hemisphere (see Fig. 1). This large stress does not contribute to the global budget of angular momentum, but may play some crucial role in a restricted area.

We now assume that tropospheric winds are consistently westerly all the year round above 650 mb level over the circum-continental mountains. In the planetary boundary layer whose top level corresponds to about 650 mb, weak easterly winds are seen since Antarctica is covered by a high pressure system. Gravity waves induced by the easterly cannot propagate upward due to a critical level absorption. On the other hand, gravity waves induced by the westerly in the free atmosphere can propagate upward to the stratosphere without serious attenuation. Owing to extremely poor data accumulation and analysis of wind characteristics, we have no idea which part of the gravity waves is more predominantly generated. Nonetheless, we can look at some pieces of the evidence for generation of upward propagating gravity waves in the preliminary results of recent GCM simulations including gravity wave effects.

Orographic gravity waves with large amplitudes are likely to be saturated when

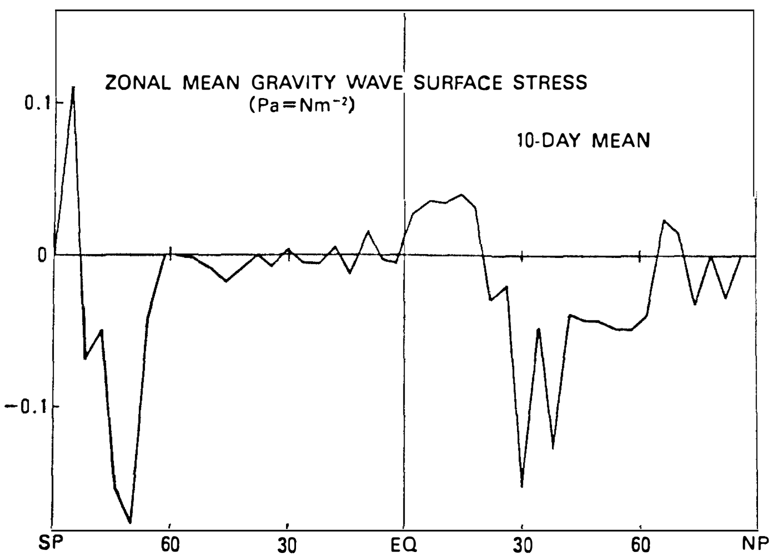

Fig. 1. Latitudinal distribution of the 10-day averaged zonal mean surface gravity wave stresses obtained from a GCM simulation (TANAKA et al., 1987).

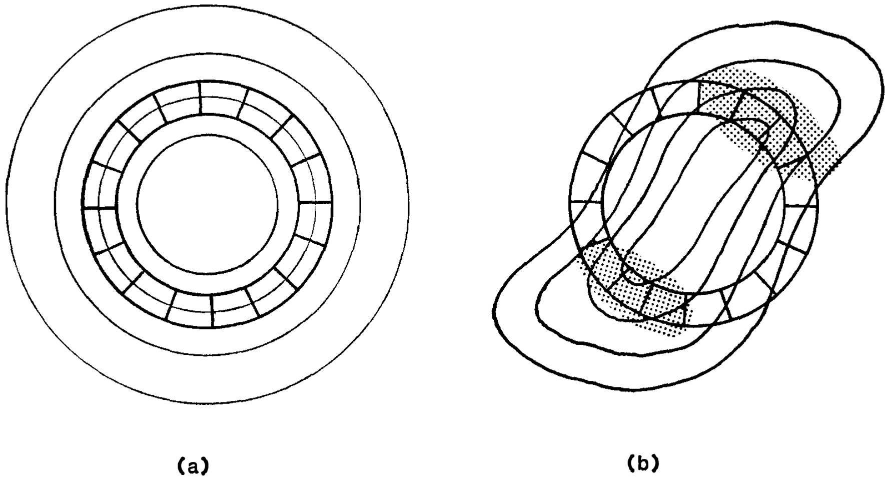

Fig. 2. Schematic illustrations for suppression mechanism of planetary wave activity by gravity wave saturation. Circular areas show the circum-continental mountain (or cliff) belts. Zonal wind decelerations are expected in the shaded areas.
(a) Circular zonal flow without embedded planetary wave.
(b) Elongated circulation due to an embedded planetary wave.

and where total flows (mean plus planetary wave components) become weak in the zonal direction, in other words, when and where zonal wind components of planetary waves cancel the large zonal background flow. A possible mechanism for suppression of the planetary wave activity is schematically shown in Fig. 2. When no planetary wave is embedded on the strong background zonal flow, gravity waves are hardly saturated since intrinsic phase velocities (difference between phase velocity and zonal wind velocity) of gravity waves are much larger than gravity wave amplitudes (see Fig. 2a). When a planetary wave (with wavenumber 2 for example) is embedded on the background zonal flow, the circumpolar circulation is elongated as shown in Fig. 2b. Zonal components of the wind velocity are decelerated mainly in the two shaded areas (see Fig. 2b) since they become close to zero, in other words, total wind directions become nearly perpendicular to wavenumber vectors of gravity waves. Then further development of the elongation is suppressed. The deceleration areas increase in proportion to gravity wave amplitudes. Note that gravity wave saturation does not occur uniformly around the pole but highly depends on the wavenumber, amplitude and phase of planetary waves.

As a result, a cavity, in which the planetary wave activity is weak, is formed in the lower stratosphere around the South Pole. As stated above, the cavity is not perfectly circular reflecting the planetary wave structure (see Fig. 2b). Significant amount of the heat flow associated with the planetary wave is expected to be suppressed in the lower stratosphere until the final warming breaks the cavity. Some gravity waves with small amplitudes, which pass through the lower stratosphere without saturation, finally encounter a wind reversal level existing in the middle stratosphere during late spring and totally break there since the wind reversal level is a critical level for orographic gravity waves.

Meridional circulations induced in the cavity are poleward and then turn to both upward and downward near the South Pole. This circulation partly contributes to

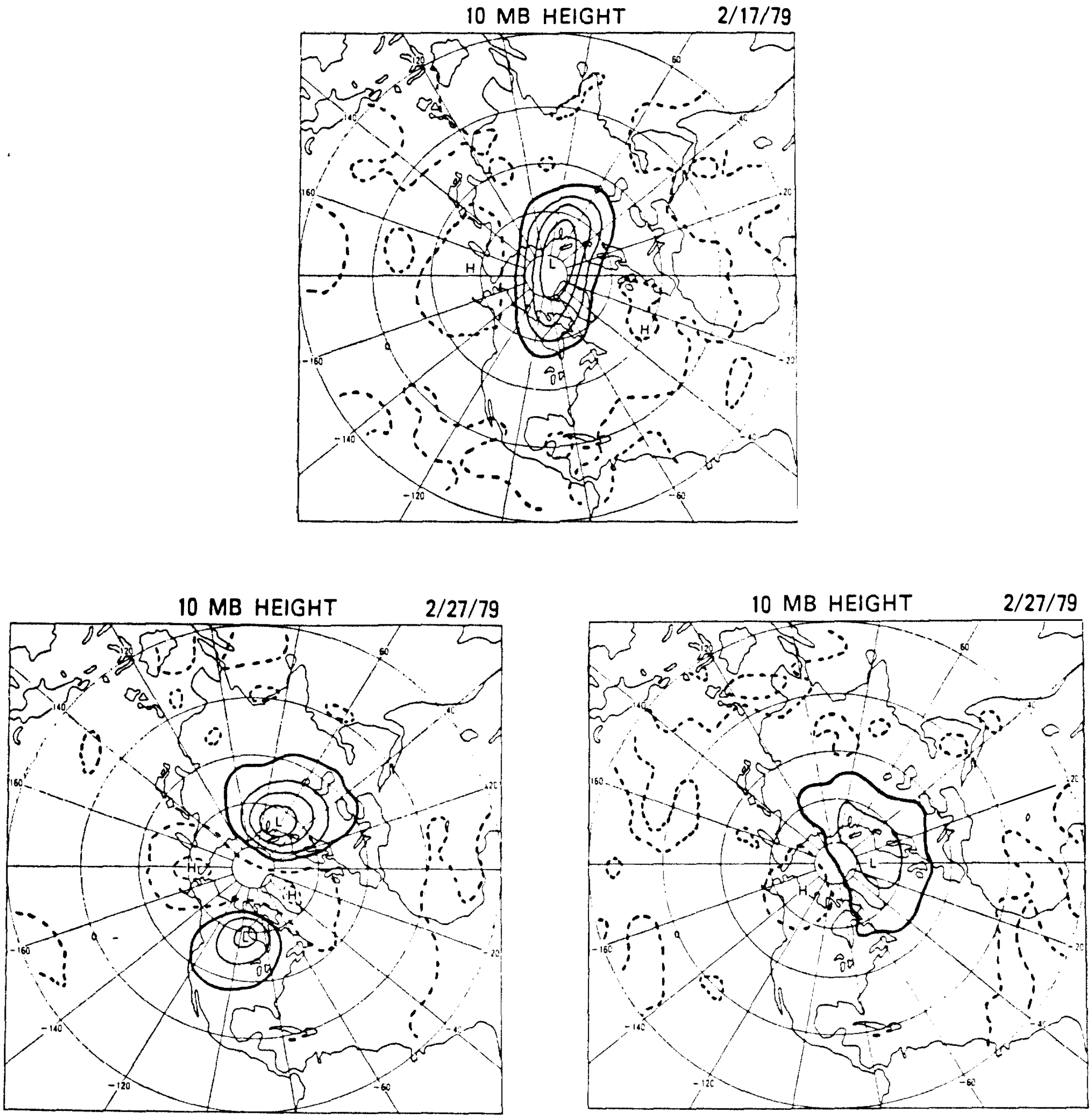

Fig. 3. Height maps of 10 mb in the northern hemisphere forecast by the GMC during a major stratospheric warming. Top panel shows initial condition on 2/17/1979. Bottom panels show the forecast results on 2/27/1979 without (left) and with (right) gravity wave parameterization. Thick solid, 30500 m; thin solid, 30000, 29500, 29000 m; thick dotted, 31000 m; thin dotted, 31500 m.

the adiabatic change of temperature. Wave transience may accelerate formation of the cavity but it is still not clear how rapidly the gravity waves change the amplitude. Along this scenario a numerical simulation is now planned using a mechanistic model.

Here we show an example of the northern hemisphere how planetary waves are affected and modulated by gravity waves emitted from mountainous Greenland. Gravity waves are impulsively switched on a GCM at an initial instant. Note that this situation can be realized artificially in a numerical model and does not usually occur in the actual atmosphere except under special circumstances. The forecasted height maps of 10 mb are shown in Fig. 3 on 2/17/1979 (initial value) and 2/27/1979 for the cases without and with gravity wave parameterization. The GCM without gravity wave parameterization simulates well the breakup of circumpolar vortex and its transformation to a typical major warming pattern with wavenumber 2 while the GCM with gravity wave parameterization does not show such a pattern. The typical minor warming pattern with wavenumber 1 is formed at the very early stage of time-integration and lasted consistently. The vortex over Canada (including Alaska and Greenland) totally disappears by the transient effect of fully amplified gravity wave fronts. The mismatching which appears in the model start-up procedure should be carefully removed particularly in the polar region. However, this result also shows that gravity waves, if the amplitudes change rapidly in time no more than a day in the actual atmosphere, can seriously modify the planetary waves and reduce associated warming in the stratosphere.

4. Concluding Remarks

Suppression of planetary wave activity due to gravity wave saturation is proposed as a possible mechanism for maintaining a low temperature environment in the Antarctic lower stratosphere. This idea is not widely accepted since interactions between gravity waves and planetary waves are a concept which appeared quite recently.

An important key for the solution of the dramatic ozone hole events seems to be concealed in the troposphere. Increase of sea surface temperature surrounding Antarctica, if any, may decelerate the easterly wind in the planetary boundary layer over Antarctica and generate the westerly wind along the continental coast. This situation is in favor of generation of upwardly propagatable gravity waves. Anyhow, a long-term trend of wind systems and gravity wave activity for the past several years should be analyzed in the polar region, together with detection of the planetary wave activity and other signals of polar climate change.

The present proposal is partly based on the paper by TANAKA *et al.* (1987) which was originally written for other purposes. None of the co-authors of the paper are responsible for this proposal. The references, except for the latest several papers, are omitted even if they are important.

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