~~APPENDIX A~~

MASTER

PLANETARY-WAVE BEHAVIOR AND ARCTIC AIR POLLUTION

by

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Abstract

An attempt has been made to relate episodes of air pollution at Barrow, Alaska, containing vanadium, to the behavior of planetary waves in middle and high latitudes. A stationarity index for planetary waves is defined as the ratio between amplitudes computed from monthly mean maps and the mean amplitudes computed on a daily basis and averaged over the same month, irrespective of phase angle. Longitude-time sections of 500-mb height anomalies at various latitudes are related to vanadium pollution episodes at Barrow.

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1. Hypothesis

On occasion the Arctic regions near Point Barrow, Alaska, experience relatively high concentrations of vanadium (V) in air pollution. Since V is a trace element found in heavy residual oils it could not have been injected into the atmosphere locally but had to originate in industrial burning operations, most likely in oil-fired power plants in midlatitudes (Zoller et al., 1973). The New England states and Europe are among the most likely source areas of V (Rahn and McCaffrey, 1979).

If such midlatitude sources, indeed, were responsible for V in Arctic air pollution one will have to search for transport processes, preferably in the lower troposphere, which are capable of importing V into the Arctic without excessive cleansing of the air by washout and rainout. One can assume that such transport processes, if their existence can be demonstrated, will also carry aerosol components other than V which might contribute significantly to Arctic haze. Such haze may influence radiation fluxes and therefore might be of concern to climatologists, especially if its existence were widespread and long lasting.

Washout and rainout processes during winter in temperate latitudes are mainly connected with frontal precipitation which, in turn, is connected with the passage of baroclinic wave disturbances of cyclone scale. In our search for transport processes that might be responsible for long-distance advection of V without much wet deposition we decided, therefore, to concentrate on the characteristics of long and ultra-long quasi-barotropic planetary waves and to filter out the much shorter cyclone waves.

2. Planetary Wave Characteristics.

A low-order (truncated) spectral resolution of the 500-mb height field provides the easiest approach to filter planetary long and ultra-long waves from the rest of the atmospheric disturbances. The assumption of quasi-geostrophic flow to prevail above the planetary boundary layer lets us interpret geopotential height gradients on isobaric surfaces in terms of winds, hence in terms of mass and pollution transport (if pollution concentrations near the source were known).

Harmonic decomposition of a geopotential height field around a certain latitude circle can be expressed as:

$$Z_n(\lambda, \phi, t) = Z_0(\phi, t) + \sum_{n=1}^N A_n(\phi, t) \cos[n\lambda + \psi_n(\phi, t)] \quad (1)$$

Z_n is the time-dependent contribution of wave number n to the geopotential height field at latitude ϕ and longitude λ . Z_0 is the (time-dependent) mean height at that latitude, A_n is the amplitude and ψ_n the phase of the n^{th} harmonic.

On a daily basis $A_n(\phi, t)$ and $\psi_n(\phi, t)$ describe each planetary-wave pattern.

Planetary waves can also be computed from monthly-mean geopotential height data. The waves thus computed are the so-called standing-wave components. The transient waves have been filtered out by the time-averaging process:

$$\overline{Z_n}(\lambda, \phi, \hat{t}) = \overline{Z_0}(\phi, \hat{t}) + \sum_{n=1}^N \overline{A_n}(\phi, \hat{t}) \cos[n\lambda - \overline{\psi_n}(\phi, \hat{t})] \quad (2)$$

The overbar indicates an averaging process with respect to time over, say, one month, and $\hat{t}$ symbolizes variability on a time scale exceeding that averaging period.

For completely stationary planetary waves the monthly means of their daily amplitudes should be the same as the amplitudes calculated from the monthly mean height patterns. If, on the other hand, the waves are mobile, $\overline{A_n(\phi, \hat{t})} < \overline{A_n(\phi, t)}$. As a matter of fact, if $\psi_n(\phi, t)$ varied randomly over 360° or 2π during the course of one month, and if $\psi_n(\phi, t)$ were uncorrelated with $A_n(\phi, t)$, the summation term in Eq. (2) would be zero.

We can define the Stationarity Index of the n^{th} harmonic as

$$SI_n = \frac{\overline{A_n(\phi, \hat{t})}}{\overline{A_n(\phi, t)}} \quad (3)$$

This index can vary between 1 (for completely stationary waves) and 0 (for waves sweeping over full cycles of 360°).

Each planetary wave, as a function of latitude and time, can now be characterized by three parameters

- (1) Its amplitude, $A_n(\phi, t)$.
- (2) Its mean phase position, $\psi_n(\phi, t)$.
- (3) Its relative mobility or stationarity during the time-period of averaging, e.g. one month, given by SI_n .

All three parameters will be needed to assess the impact of planetary-wave behavior on Arctic pollution episodes.

3. Interannual Variability of Planetary-Wave Characteristics.

We have performed harmonic analyses of the daily 500-mb height fields along latitude circles between 20°N and 80°N in the manner indicated in the preceding chapter. Only a few examples of these analyses are shown here. We have chosen the 45th parallel as the latitude circle representing the New England states which are suspected as a source of vanadium from the burning of heavy residual oils. The European industrial regions also lie near this geographic latitude. Most of the Japanese industrial regions are closer to 35°N than 45°N.

Figure 1 illustrates the behavior of monthly mean values of $\overline{A_n(\phi, t)}$ (thin line) at 45°N, i.e. the monthly mean value of the daily amplitudes of wave number 1 averaged irrespective of phase angle. The heavier line in this diagram represents the results after application of a low-pass filter with a 0.065 month⁻¹ cut-off frequency. The period equivalent to that frequency is approximately 15 months. This filter suppresses almost all of the annual cycle and shorter periodicities, but leaves variations on an interannual time scale nearly unchanged.

Figure 1 reveals a strong annual cycle in wave number 1, with maximum amplitudes during winter. It becomes quite obvious from this diagram that neither the maximum monthly average amplitude of this wave number, nor the month of its occurrence, remain the same each year. The interannual variability of the average amplitude is well expressed by the filtered curve. There is, however, some aliasing of the peaks in the filtered curve when compared against the months in which the actual maximum of $\overline{A_1(\phi, t)}$ occurred.

On occasion we notice a sharp decrease of the amplitude $\overline{A_1(\phi, t)}$ in mid-winter, for example in January 1963, February 1966, January 1970,

1971 and 1973. These decreases seem to coincide with cases of polar-vortex breakdowns and major stratospheric warmings. According to Labitzke's (1977) study, major warming events are accompanied by a rapid decrease of the amplitude of wave number 1 from a pre-warming maximum value. Wave number 2, on the other hand, increases rapidly during the warming period from a pre-breakdown minimum.

We also found marked seasonal cycles in $\overline{A_n(\phi, t)}$ for wave numbers 2, 3 and 4 whose amplitudes undergo strong interannual trends (not shown here). Wave numbers 5 and 6 reveal a relatively more noisy pattern of monthly amplitude values. A seasonal cycle is still discernible, but month-to-month variations seem to dominate the behavior of these planetary long waves.

The mobility of planetary waves can be depicted by monthly values of SI_n . Examples, again at $45^\circ N$, are provided in Fig. 2. Wave number 1 shows only a very weak seasonal cycle in this ratio. The month-to-month variability of this parameter reveals the fact that this ultra-long planetary wave can shift from nearly stationary conditions to nearly complete cycling in a one-month period. Some long-term trends are also indicated in Fig. 2. Wave number 1 appeared to be more stationary during the early 1950's than during the early 1960's.

Wave number 2 (Fig. 3) reveals somewhat more of an annual cycle in its stationarity aspects than wave number 1. Maximum stationarity tends to occur during the winter season. Similar conditions seem to dominate the mobility of wave number 3 (not shown here). Higher wave numbers, in general, tend to be less stationary, revealing smaller average values of the index SI_n . Seasonal cycles in these ratios for wave numbers 4 and 5 are difficult to discern. Wave number 6 reveals a trend towards greater stability in summer than in winter.

5. Meridional Mass Transport by Ultra-Long and Long Planetary Waves.

Wave numbers 5 and 6 reveal considerable phase-angle fluctuations on time scales of a few days, meaning that these waves vacillate considerably in their positions. These fluctuations are caused mainly by transient baroclinic disturbance of cyclone scales (wave numbers of the order of 12 or more in midlatitudes) which travel through the long-wave pattern, thereby distorting it and causing shifts in its harmonic phase angles.

In order to emphasize those aspects of the planetary wave patterns that remain nearly stationary over time periods of several days and therefore could lead to the observed fluctuations of vanadium concentrations in the Arctic, we decided to truncate the harmonic recomposition of the 500-mb pressure patterns with planetary wave number 4.

Figure 4 shows time sections of 500-mb height anomalies, derived by summing the first four harmonics

$$Z = \sum_{n=1}^4 A_n \cos(n\lambda - \phi_n) \quad (7)$$

on a daily basis and then computing consecutive 5-day averages of this low-order spectral resolution of the daily height fields. Sections are shown for 45°N, 55°N, 65°N and 75°N. Episodes of high and low vanadium pollution at Point Barrow, Alaska, (Rahn and McCaffrey, 1979) are also indicated in this figure. We should note that suspected North American sources lie in the longitude region 70-80°W. European sources, most likely, are concentrated between 10°W and 20°E. Japanese sources, if any, would lie between 130 and 150°E. Vanadium pollution in the Arctic should be preceded by southwesterly planetary long-wave flow over any of these regions. That means that near 45°N the high anomalies shown in

Fig. 4 should have a preference of transition from trough (negative values) to ridge (positive values) over one or any of the suspected source regions. Point Barrow, Alaska, lies in the 150° to 160° W longitude sector at 70° N.

Planetary waves 1 to 4, shown in Fig. 4, supposedly are quasi-stationary since they are mainly produced by orographic forcing. Indeed, we find the prevalence of a major trough in the longitude region of the date line (180° E). Another trough settles in the region around 70° W and a third, minor trough appears off and on near 20° E. Major ridges occupy the regions near 80° E, 120° W and 0° . The amplitudes of this truncated planetary-wave height field undergo significant changes with time. Major amplitude maxima along trough and ridge lines tend to lie 20 to 30 days apart, indicative of the amplitude vacillation of planetary waves described by McGuirk and Reiter (1976).

The interesting conclusion can be drawn from this diagram that the "quasi-stationary" planetary waves are all but stationary. They undergo periods of rapid upheaval in the form of progression, retrogression or new development (Barrett, 1961).

Episodes of low vanadium concentrations at Barrow are preceded by 5 to 10 days by a negative pressure anomaly of < -100 m at 45° N and 150° W. In several instances this eastward extension of the trough influence region (whose center normally lies near 160 to 170° E) is followed by the development of a ridge with pressure anomalies > 100 m centered between 140° W and 120° W. Quite obviously, such trough extensions into the Gulf of Alaska, together with the development of high-pressure ridges over, or off, the North American west coast, produce southerly flow over Alaska, importing relatively clean oceanic (Pacific) air masses into the Point Barrow region.

Heavily polluted episodes, on the other hand, are preceded 15 to 20 days by stronger-than-normal troughs between 80°W and 60°W , i.e. over, or slightly to the east of, the New England states. Stronger-than-normal ridge development to the east of these trough locations, i.e. over the Atlantic near 20°W also provides favorable conditions for pollution import into the Arctic regions under southerly flow conditions. Dashed lines in Fig. 4a indicate the possible connections between such trough and ridge developments with Arctic pollution episodes.

At 55°N (Fig. 4b) major troughs off the North American east coast and blocking high-pressure ridges over the central North Atlantic (ca. 30°W) tend to be favorable precursors to pollution episodes at Barrow Alaska. (Dashed lines in Fig. 4b give an indication of such connections between southerly flow over the Atlantic and pollution episodes in northern Alaska.)

The longitude-time section of 500-mb heights at 65°N (Fig. 4c) offers a mixture of middle- and high-latitude wave patterns, which are difficult to relate to pollution episodes at Barrows. There is an indication that near 100°W , prior to the arrival of vanadium-containing pollution at that station, transitions from anticyclonic to cyclonic regimes occur.

As one proceeds to even higher latitudes (75°N , Fig. 4d) transient wave modes begin to dominate the 500-mb height field. Some of these waves appear to have a slowly retrogressive tendency, indicated by the "slope" of trough axes from right to left. In Fig. 4d we have attempted to indicate such trough retrogressions by dashed lines. Major vanadium pollution episodes at Barrow (Rahn and McCaffrey, 1979) have a tendency to occur when such westward moving troughs pass the longitude sector of

Barrow. An exception is the pollution episode of 31 December, 1977 to 10 January, 1978. For this period, however, the contour analysis of Fig. 4d cannot be considered reliable. It was patched together from separate analyses for the years 1977 and 1978.

5. Conclusions

A quantitative assessment of the possible midlatitude sources of the vanadium encountered at Barrow, Alaska, will have to rely on trajectory calculations, using low-tropospheric wind data. The planetary-wave analyses presented above cannot replace such detailed trajectory computations. They can, however, help in identifying those large-scale flow patterns in middle and high latitudes, which are primary suspects of importing pollutants and haze into the Arctic regions. Since, as has been mentioned in Section 3, planetary waves reveal a considerable interannual variability, we should expect some variability in Arctic pollution -- even with midlatitude sources assumed as constant.

The trough-ridge patterns described for middle and high latitudes in Fig. 4, and accused of providing a transport channel mainly from the New England states to the Arctic regions, are reminiscent of harmonic pattern sequences analyzed by Barrett (1961). Figure 5 shows the contributions of the first harmonic (wave number 1) to the mean 300-mb height patterns for January-February 1949. The spiral shape of this first harmonic contribution, according to Barrett, also relates to the mean jet-stream pattern. Planetary wave number 1, thus, appears to establish a preferred pollution transport channel from the northeastern United States into the Arctic regions. This channel is modulated by wave number 2 and higher wave numbers of more transient character.

Even though the evidence presented here, and especially in Fig. 4, points towards the New England states as the suspected source regions for vanadium observed in the Barrow, Alaska, region, northern European sources cannot be ruled out altogether since they lie within the same spiralling transport channel shown in Fig. 5.

References

- Barrett, E.W., 1961: Some applications of harmonic analysis to the study of the general circulation. Pt. 1; Beiträge Phys. Atmos. 33, 280-332.
- Labitzke, K., 1977: Interannual variability of the winter stratosphere in the northern hemisphere. Mon. Wea. Rev., 105 (6), 762-770.
- McGuirk, J.P. and E.R. Reiter, 1976: A vacillation in atmospheric energy parameters. J. Atmos. Sci., 33 (11), 2079-2093.
- Rahn, K.A. and R.J. McCaffrey, 1979: Long-range transport of pollution aerosol to the Arctic: A problem without borders. Paper presented at the WMO Symposium on Long-Range Transport of Pollutants and its Relation to General Circulation, Including Stratospheric/Tropospheric Exchange Processes, Sofia, Bulgaria, 1-5 October 1979.
- Zoller, W.H., G.E. Gordon, E.S. Gladney and A.G. Jones, 1973: The sources and distribution of vanadium in the atmosphere. In: Trace Elements in the Environment. Advances in Chemistry Series, No. 123, American Chemical Society, Washington, D.C., pp. 31-47.

Fig. 1 Monthly mean values of $\overline{A_n(\phi, t)}$ for wave number 1, 500-mb heights in meters at 45°N (thin line). Slightly heavier line: low-pass filtered data with filter cut-off at period of 15 months.

Fig. 2 Ratios SI_n , computed on a monthly basis, for wave number 1, 500-mb heights, at $45^\circ N$ (thin line). Slightly heavier line: low-pass filtered data with filter cut-off at period of 15 months.

Fig. 3 Similar to Fig. 2, except for wave number 2.

Fig. 4 Longitude-time sections of the contributions to the 500-mb height pattern (analyzed in 50-gpm increments negative values dashed) by planetary wave numbers 1, 2, 3 and 4, for latitudes as indicated on individual diagrams. Heavy horizontal dashes between 1977 and 1978 indicate inspected vanadium source regions in the longitude sectors of Europe, Japan, and the eastern U.S., as well the target region of Barrow, Alaska (two dots). On the right margin of each diagram episodes of high (thick vertical lines) and low (thin vertical lines) vanadium concentrations at Barrow are indicated. For explanation of slanting dashed lines, see text.

B.

55 DEGREES LATITUDE

Fig. 4 (Continued)

Fig. 4 (Continued)

Fig. 4 (Continued)

Fig. 5 Mean pattern of the first harmonic of 300-mb heights, January-February 1959 (Barrett, 1961).