NWS-TA-CR-95-16

CRH SSD
SEPTEMBER 1995

CENTRAL REGION TECHNICAL ATTACHMENT 95-16

APPLICATION OF ROSSBY WAVE THEORY TO DIAGNOSING AND PREDICTING REAL-TIME PLANETARY-SCALE REGIMES BOTH OBSERVATIONALLY AND NUMERICALLY

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1. Introduction

The type of wave motion that is most important for understanding and analyzing large-scale dynamical atmospheric processes is Rossby wave, also called planetary waves. Planetary waves have also been called Rossby-Haurwitz waves, since Haurwitz (1940) extended Rossby's ideas to spherical geometry. This terminology is applied to quasi-horizontal atmospheric (and oceanic) wave motions whose shape, wavelength and displacements are governed by the variation of the Coriolis parameter with latitude (Rossby 1939, 1945; Ekman 1932, Holton 1992).

A basic understanding of some concepts of Rossby wave dynamics can be a useful operational forecast tool. That includes diagnosing curved baroclinic energy propagations, the speed of energy propagations, identification of teleconnection patterns such as the PNA, NAO and TNH (Berry 1995a,b,c) and evaluating numerical model guidance (for all time/space scales). The purposes of this Technical Attachment (TA) are to 1) illustrate to forecasters how to identify real-time Rossby ray traces, and 2) to use that information to assess numerical model guidance. Several papers from the literature will be cited, where additional details of the following can be found.

2. Background on Rossby Wave Theory

In an inviscid (molecular viscosity of the air is zero (Bluestein 1992)) barotropic fluid of constant depth, the Rossby wave is an absolute vorticity-conserving motion that owes its existence to the latitudinal variation of the Coriolis force (the Beta effect). More generally, in a baroclinic atmosphere the Rossby wave is a potential vorticity-conserving motion that owes its existence to the isentropic gradient of potential vorticity (Holton 1992 and Hoskins et al. 1985).

In 1939, Rossby theoretically demonstrated these ideas with a simplified wave equation, which distilled atmospheric dynamics to its barest essence (Tribbia 1991). That is the familiar barotropic vorticity equation, which can be written as follows, in Cartesian coordinates

$$\left(\frac{\partial}{\partial t} + u\frac{\partial}{\partial x} v\frac{\partial}{\partial y}\right)\zeta + \beta v = 0 \qquad (1)$$

where u=dx/dt and v=dy/dt are the x and y components of the wind velocity, [ζ] is the relative vorticity and [β=df/dy] is Beta. Lower case f is the Coriolis parameter. From (1), the following Rossby wave zonal phase speed relationship can be derived

$$C_x - \bar{u} = -\beta/K^2 \qquad (2)$$

where K**2 is the total wave number squared, Cx is the total zonal phase speed (speed of the Rossby wave relative to the ground) and ū is the speed of the mean flow. Total wave number is defined as k**2 (zonal) + l**2 (meridional).

Additional details of the above can be found in Holton (1992). While many forecasters have seen this presentation previously, including doing some computations, they may not be familiar with its physical interpretations.

A first principle ramification of the above is whether atmospheric waves (think of 500-mb as a reference) will progress, retrogress or remain fixed. As many readers may recall, as the wavelength between the troughs and ridges increases, the advection of planetary (earth's) vorticity by the mean flow increases, thus making the features more retrogressive. If the advection of earth's vorticity by the mean flow is greater than the advection of relative vorticity, there may be retrogression (other "factors" need to be considered when discussing the real atmosphere).

Generally speaking, zonal wave numbers 3 or greater are progressive while 1 and 2 are retrogressive. However, this movement is **relative to the ground. Rossby wave zonal phase propagation is always westward relative to the mean zonal flow (Holton 1992).**

Now what about the characteristics of baroclinic energy propagations, and understanding how the atmosphere may respond to localized external remote forcing (orographic and diabatic)? Furthermore, what about the dynamics of teleconnection structures such as the PNA, NAO and TNH? This is all in the presence of an atmosphere where there is a latitudinal variation of the Coriolis parameter and spherical geometry applies.

Before continuing, understand orographic forcing is meant to describe sources of relative vorticity (cyclonic and anticyclonic) due to features such as large mountain ranges (ex. Himalayas, Andes and Rockies) and plateaus (such as the Tibetan). Diabatic forcing means to suggest origins of relative vorticity from thermal sources, such as: large areas of enhanced equatorial deep-moist convection, sea surfaces, snow covered regions, etc. The atmosphere is very sensitive to the locations and elevations of any remote forcings, and that forcing can be from any number of sources.

From the results of numerous modeling and theoretical studies, it turns out that while the vorticity centers (and their waves) generated by orographic and thermal means propagate westward, the energy from them moves eastward, following **anticyclonically curved great circle arcs** (examples shown next section). Furthermore, the movement of the energy, at a speed equal to the group velocity of all waves present, can be quite rapid, about 30 degrees of longitude per day at 45 degrees north latitude (about three times faster than the phase speeds of synoptic-scale weather systems). Additional reading on these concepts can be found Hoskins et al. (1977) (where work was done to combine the effects of dispersion, spherical geometry, and the beta effect), Tribbia (1983), Hoskins and Ambrizzi (1993) and Clark (1979).

Further, in regard to sources of vorticity from the lower latitudes, such as the tropics, theoretical work indicates that energy for zonal wave numbers 3 or less propagates strongly polewards (both hemispheres). Higher wave numbers appear to be trapped equatorward of the poleward flank of the westerlies (Hoskins and Karoly (1981), Held (1983)).

The result of the above discussed energy propagations can be nice anti-cyclonically curved Rossby wave trains, including planetary-scale regimes favoring projections such as the PNA, NAO and TNH. If the localized remote forcing is geographically fixed, then the ensuing wave train will likely remain stationary. If the forcing is transient (low frequency time-scale, for example), then the wave train may slowly evolve from one state to another. An example of the latter is the response of the extratropical northern hemispheric westerlies during winter to the Madden-Julian Oscillation. Papers by Weickmann et al.(1985), Simmons et al. (1983), Horel and Wallace (1981), Wallace and Blackmon (1983), Jin and Hoskins (1995) and Lussky (1986) provide additional detail to the above.

Finally, baroclinic energy propagations will often follow great circle arcs, being "guided" (Hoskins and Ambrizzi 1993) by Rossby wave energy dispersion. An example is shown in the next section.

3. Examples, and Evaluating Model Predictability

The point of this section will be to illustrate Rossby ray traces. It is not the purpose to speculate on the causes of remote forcings (if any). Again, based on theory, localized remote forcings may have been present in the cases to be shown.

In regard to predictability, recall that the highest skill of the numerical models, especially after day three, comes from the planetary-scale (zonal waves 0-6, for our purposes). If there are remote forcings occurring that are affecting the planetary-scale waves, and if the models capture it (for "whatever" reasons), greater confidence may be placed in the forecast solutions of various fields ("short" and "long" ranges). Stated another way, for an ensemble, there would be less spread among the members (Berry 1995d).

A. Case 1

Figure 1 shows the 500-mb hemispheric analysis valid 0000 UTC 16 March 1995. What is important to observe is the great eccentricity to the polar vortex, which is strongly displaced toward central Asia. Overall, observationally the westerlies seem to be dominated by zonal wave number 1. Thus, this type of situation should be fairly well captured by the operational numerical models.

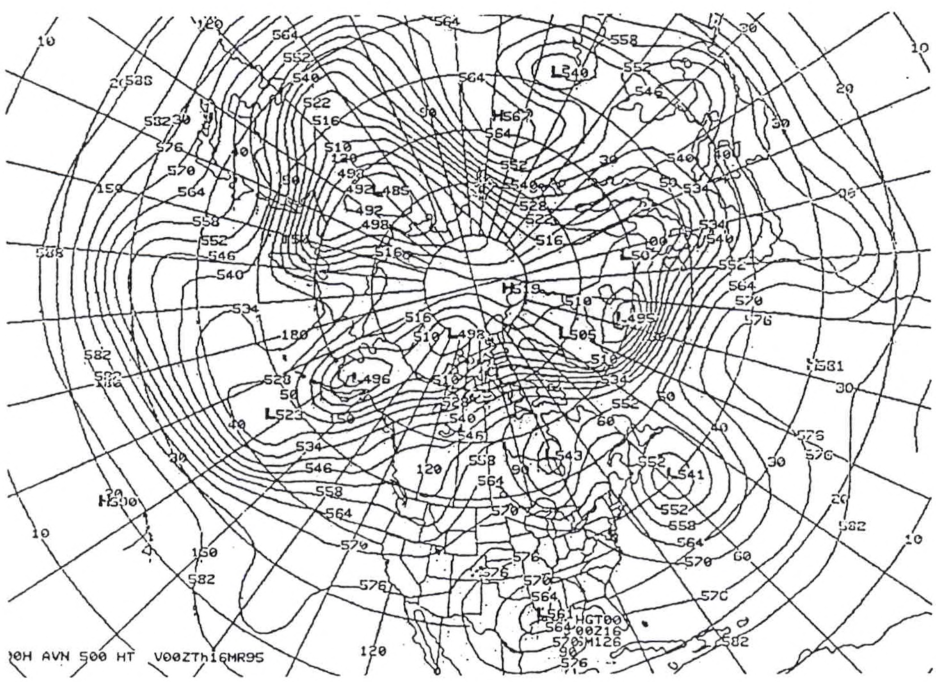

Figure 1. Northern hemispheric 500-mb geopotential height analysis valid 0000 UTC 16 March 1995. Contour interval is 6 dm.

Figure 2 is AFOS graphic W5D, the mean of the 500-mb MRF predicted height anomalies over the 5-day period from 16-21 MAR 1995. Figure 1 represents the initial conditions of what Figure 2 depicts.

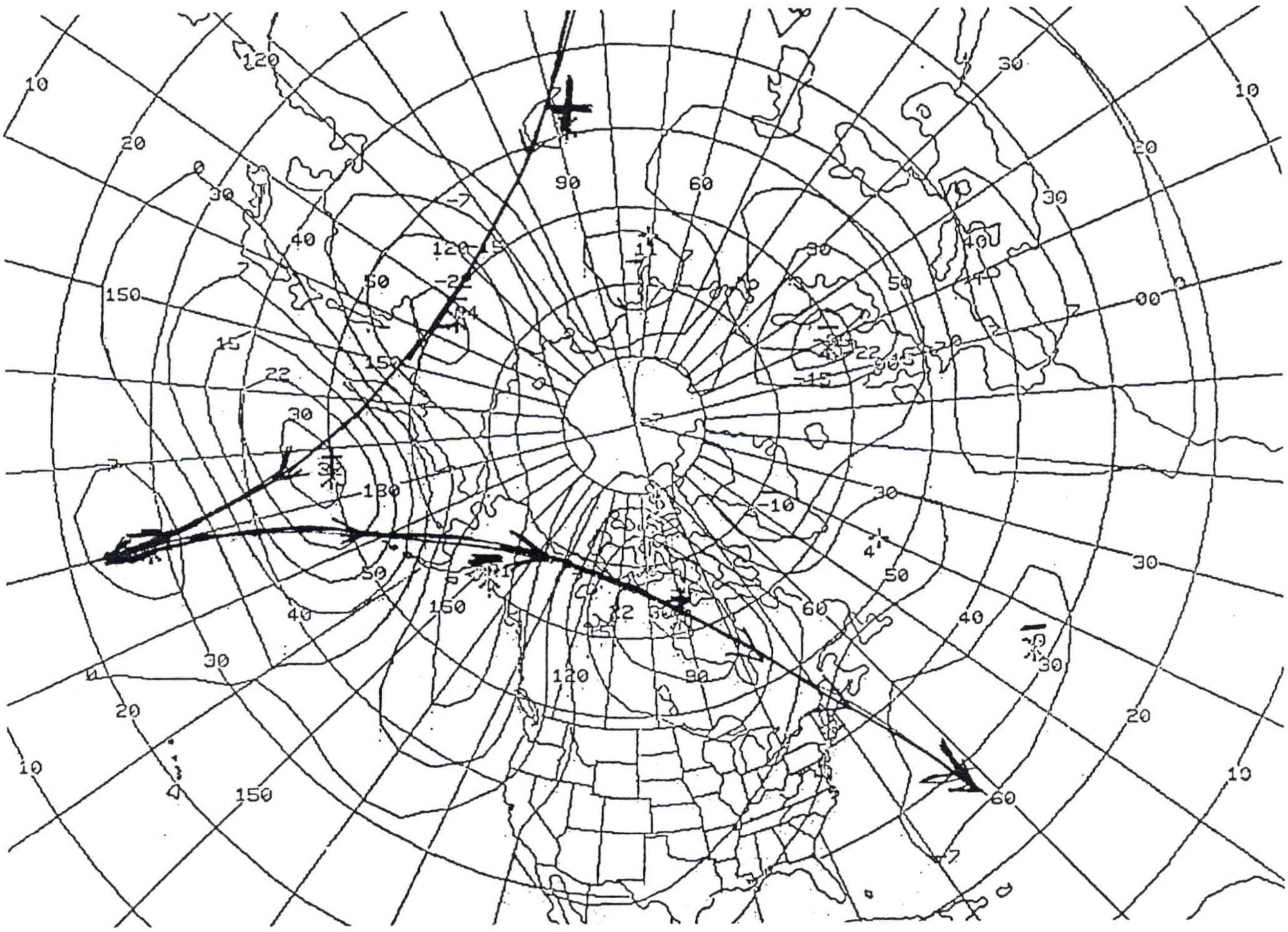

Figure 2: Five-day average of MRF model predicted 500-mb geopotential height anomalies from 16-21 March 1995. Contour interval is every 70 to 80 m, with the zero isopleth bold. Algebraic signs of the anomaly centers are given. The figure is from AFOS Western Region graphic W5D.

On Figure 2, note the areas of large positive and negative height anomalies. As shown by the arrows, at least two curved Rossby wave trains can be seen. One is from central Asia to the Dateline, and the other is from the Dateline through Canada to the western Atlantic. Given that this is a situation where the westerlies are being strongly dominated by the planetary-scale, the prediction shown in Figure 2 should be one of good confidence (for scales of motion larger than synoptic). Adding to that confidence is well "teleconnected" Rossby ray traces (a signature of the propagation of dispersive Rossby wave energy).

Apparently, the MRF model has captured the response of the atmosphere to some external remote forcing. Further, by studying the wavelengths, say between the positive height anomaly centers in Asia, at the Dateline and just north of Hudson's Bay, the response of the model atmosphere seems to be zonal wave number 4. Recall from theory that zonal wave number 4 should be deflected equatorward (by the northern flank of the westerlies), which is what the MRF was forecasting. Thus, for this case, the MRF forecast seemed reasonable. Observationally, the 5-day mean height anomaly prediction did verify fairly well.

B. Case 2

Figure 3 is the northern hemispheric 500-mb geopotential height analysis valid 1200 UTC 23 April 1995. What is important to observe is the zonal wave number 2 structure of the westerlies, with long-wave troughs around 140 degrees east and 80 degrees west longitudes. The PNA and NAO project fairly well, in the presence of the polar vortex displaced toward Asia.

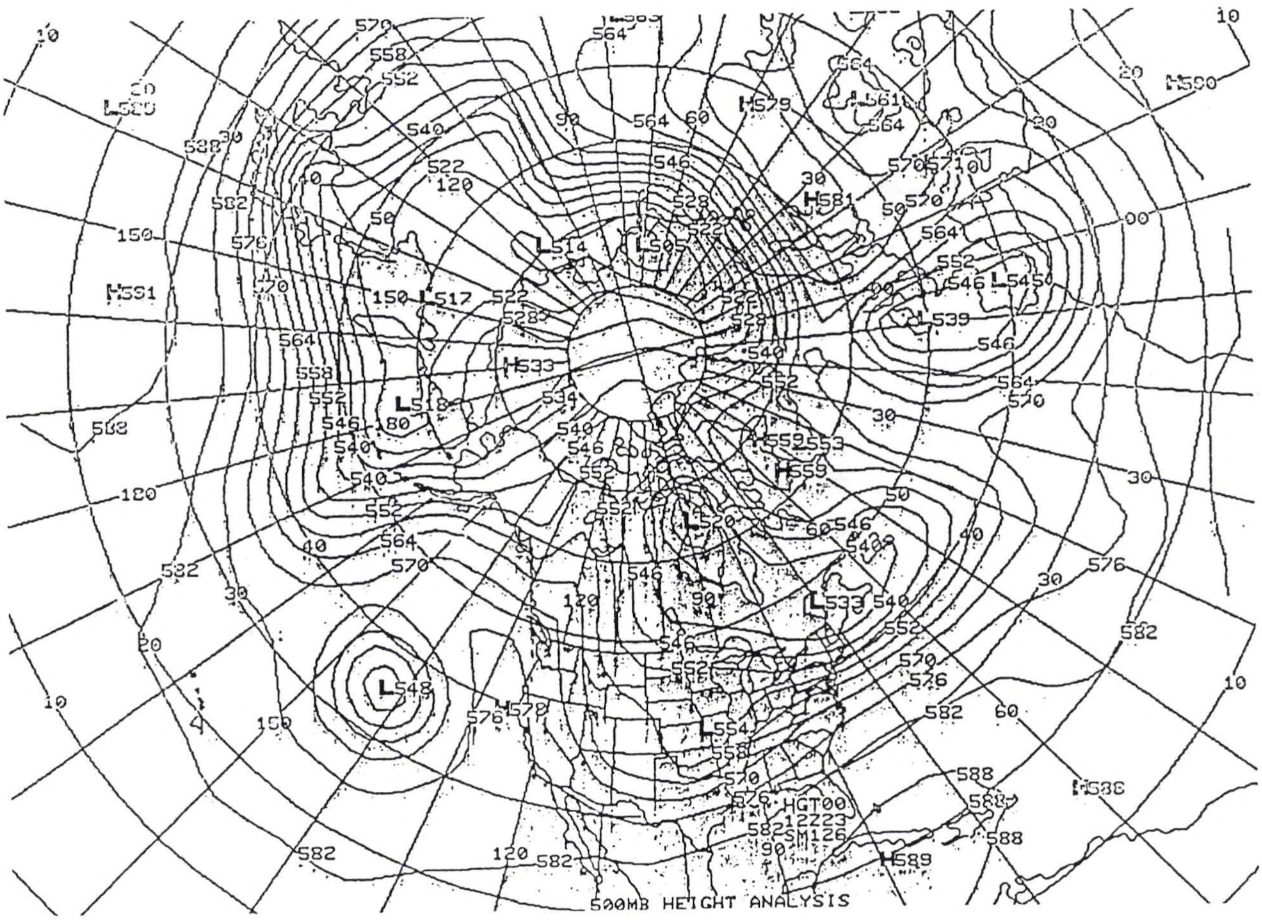

Figure 3: Same as Figure 1, but valid 1200 UTC 23 April 1995.

Figure 4 is the average of the MRF predicted height anomalies over the 5-day period from 23-28 APR. The analysis shown in Figure 3 is 12 hours after the data assimilation cycle that was utilized to generate the prediction shown in Figure 4 (which is "fine" for our purposes).

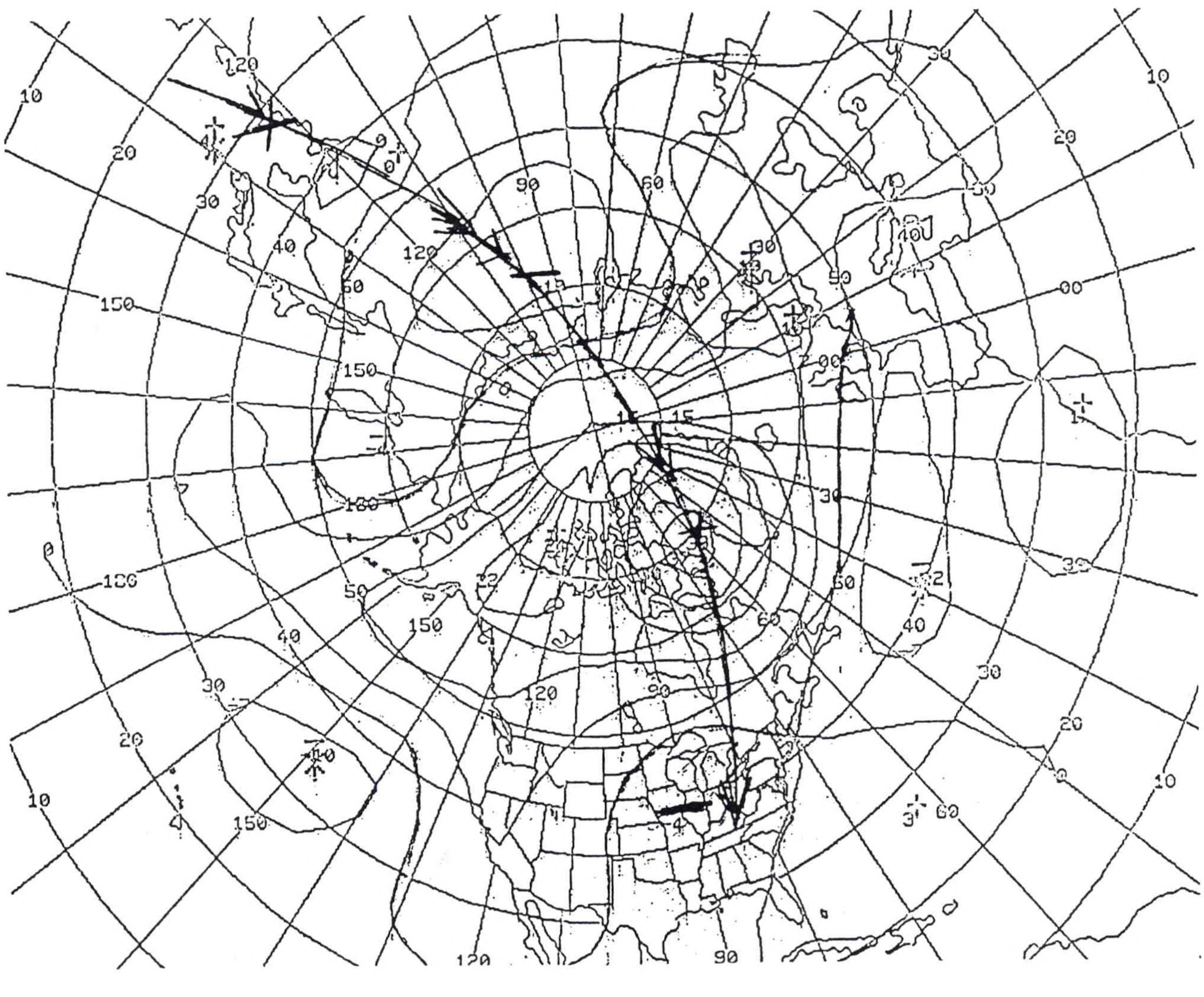

Figure 4: Same as Figure 2, but valid from 23-28 April 1995.

What is important to observe from Figure 4 is the apparent energy propagation across the North Pole from Asia to eastern North America. Judging from the spacing (about 180 degrees) between the height anomaly centers, the energy propagation appears to also be wave number 2. Again, it follows from the earlier discussed Rossby wave theory that zonal wave number 2 energy can propagate across the pole (Hoskins and Karoly 1981).

For this case, observationally, the westerlies were dominated by the planetary-scale. Further, the MRF model apparently locked on to the atmosphere's response to a localized remote forcing. Therefore the prediction shown in Figure 4 should be thought of one with good confidence, for the planetary-scale features. Indeed, the forecast shown in Figure 4 did verify fairly well.

C. Case 3

The point of this case is to illustrate the concept of curved baroclinic energy propagation in the presence of a planetary-scale Rossby wave regime. Figure 5 is the 500-mb northern hemispheric analysis of geopotential heights valid 0000 UTC 05 FEB 1995. A fairly well defined zonal wave number 3 structure of the westerlies can be seen, with the positive PNA present. The arrow depicts one possibility of Rossby wave energy dispersion.

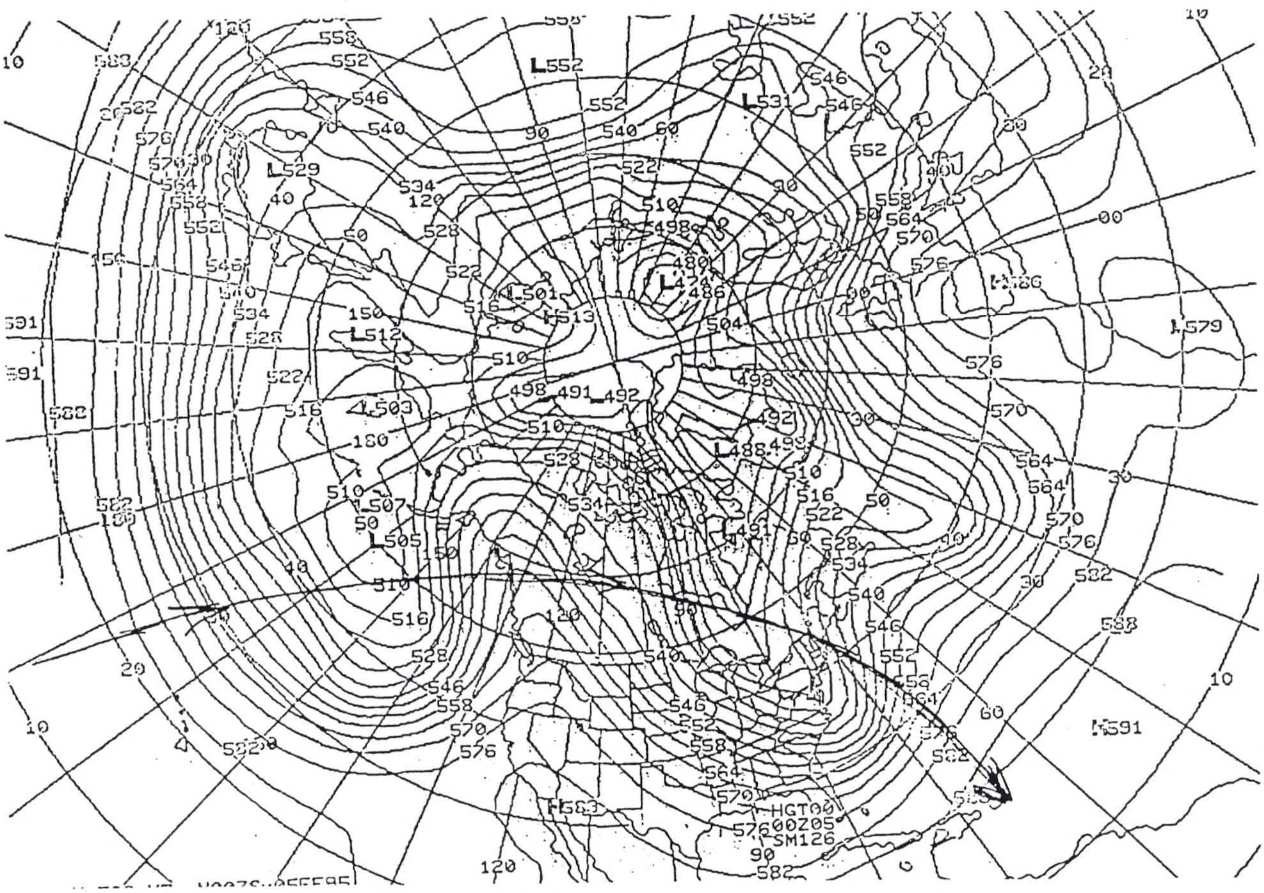

Figure 5: Same as Figure 1, but valid 0000 UTC 05 February 1995.

Figure 6 is the analysis of 24-hour 500-mb height tendencies (AFOS graphic NMCGPH5AC). The rise and fall centers should be quite apparent. The arrow connects the most likely path that baroclinic energy is propagating, at a speed with the group velocity of all the waves (recall the theory discussed above). It is easy to see that the energy propagation is not following a circle of latitude, but being guided by the Rossby wave regime. A traditional Hovmöller chart (Hovmöller 1949) would not capture this type of baroclinic energy propagation very well.

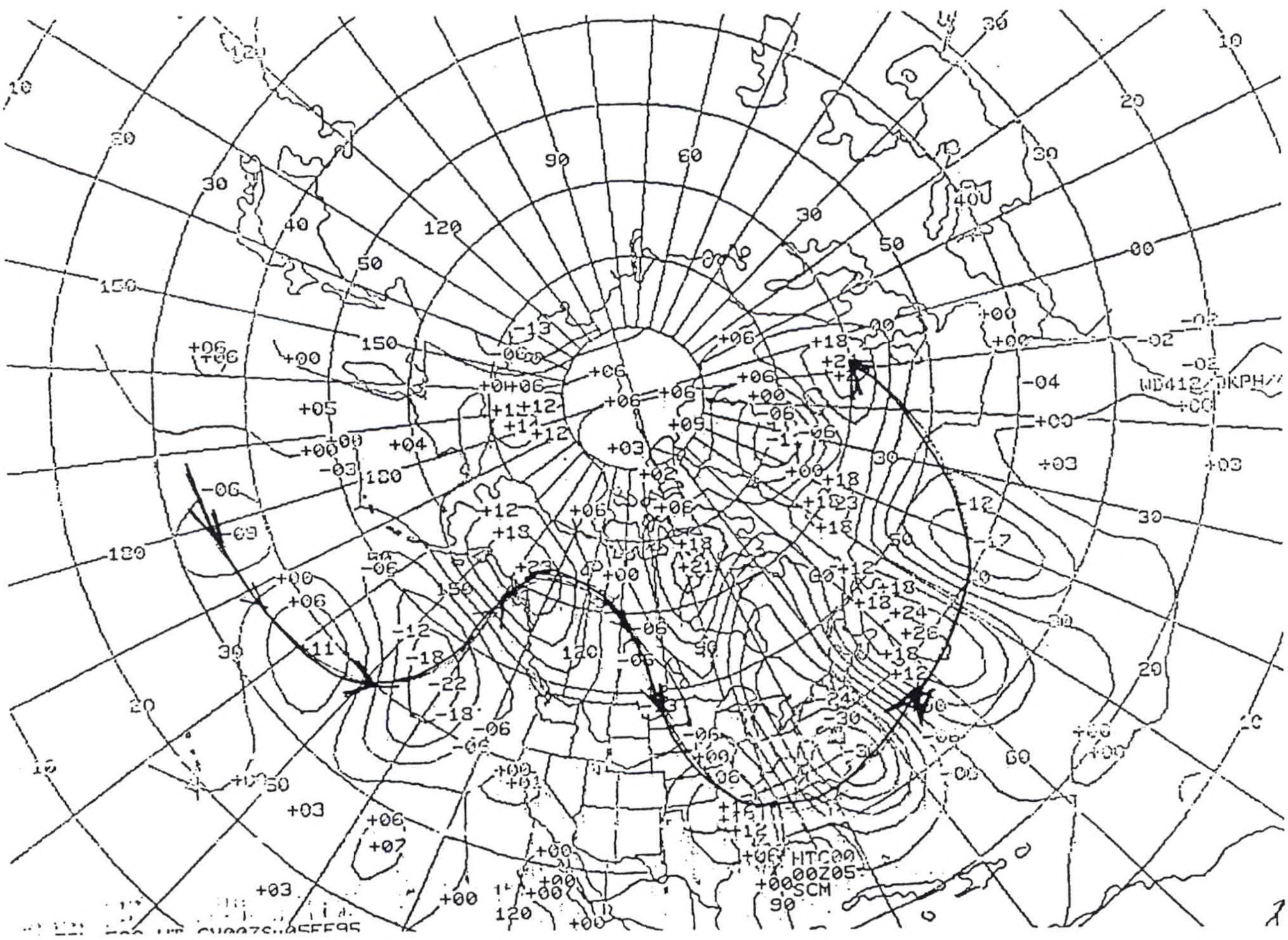

Figure 6: Twenty-four hour 500-mb height tendencies ending 0000 UTC 05 February 1995.

4. Conclusions

The purposes of this TA was to 1) illustrate to operational forecasters how to identify real-time Rossby-Haurwitz wave energy dispersions and 2) use that information to assess numerical model guidance. Three cases were shown to illustrate these points.

Important ideas to remember are that Rossby wave energy dispersion ray traces follow anticyclonically curved great circle routes, for both hemispheres. These ray traces are likely a signature of the atmosphere responding to some localized (relative to planetary-scales of motion) external remote forcings, be it thermal and/or orographic. If the operational numerical models capture this forcing, that will likely add credibility to their forecasts, for the planetary-scale. That not only includes medium- and extended-ranges (beyond day 3), but short-range as well.

Finally, baroclinic energy propagation does not always follow a circle of latitude. This propagation, in the presence of a regime where planetary-scale Rossby wave dispersion is significant, is most often curved, at speeds much greater than synoptic time-scales.

5. Acknowledgements

Appreciation is given to Richard Livingston and Preston Leftwich, Central Region SSD, for reviewing an earlier version of this paper. Deborah White-Haynes prepared the text for final publication and Michael Manker provided graphical support, both of Central Region SSD.

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