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Another look at the index cycle

By JOHN M. WALLACE and HUANG-HSIUNG HSU, *Department of Atmospheric Sciences, AK-40, University of Washington, Seattle, WA 98195, USA*

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ABSTRACT

Relationships between the zonal index, as defined by Rossby, the hemispheric circulation pattern, the amplitude of the zonally asymmetric or "eddy" component of the hemispheric circulation, and the amplitude of the stationary wave pattern during northern hemisphere winter are investigated using 27 years of gridded 5-day mean 500 mb height data from the US National Meteorological Center. In agreement with preliminary results reported in Rossby, the major stationary wave features appear to be displaced to the east of their climatological mean positions during periods of strong zonal flow, and *vice versa*. The zonal index shows only a weak negative temporal correlation with an index designed to monitor the hemispherically averaged variance of the eddy component of the 500 mb height field. Eddy amplitude is much more strongly correlated with the amplitude of the climatological mean stationary wave pattern. Hence, the notion of an "index cycle", interpreted in terms of amplitude vacillation, does not appear to have much relevance to the northern hemisphere winter-time circulation. The situation may be different in the southern hemisphere, where the stationary waves are much weaker.

1. Introduction

During the early years of the long-range forecasting project at Massachusetts Institute of Technology, Rossby and his collaborators were concerned with fluctuations in the mid-latitude westerlies in relation to longitudinal displacements of the ultra-long waves. It was this problem that motivated Rossby's theoretical analysis which resulted in the well-known dispersion relation governing the zonal propagation of one-dimensional waves in a barotropic atmosphere (Rossby, 1939). Rossby and collaborators postulated that, in accordance with this relation, the semi-permanent "centers of action" associated with the ultra-long waves forced by land-sea thermal contrasts and mountains should tend to drift westward during periods of weak zonal circulation and vice versa; and, if the displacements from their climatological mean positions become sufficiently large, new centers should form to take their place. In support of this hypothesis, Rossby (1939) showed that intensity of the westerlies, as indicated by the zonally-averaged sea-level pressure difference between 35° N and 55° N was correlated with the longitude of the Aleutian low during the 1938–39 winter. During episodes of weak westerlies within that winter, the Aleutian low was located as far west as 160° E, whereas during episodes of more intense westerlies it was found to be located as far east as 160° W.

A complementary aspect of low frequency variability of the general circulation that was emphasized in the later years of the MIT project was the apparent tendency for "high index" situations (as defined by the meridional pressure gradient in the latitude belt between 35° N and 55° N) to be characterized by abnormally warm temperatures in middle latitudes, strong high latitude baroclinity, and a poleward displacement of the zonally-averaged jetstream relative to its usual position; and low index situations to be characterized by an expanded polar vortex with strong mid-latitude baroclinity and strong westerlies near 30° N [Willett (1948), Rossby and Willett (1948)].

Lorenz (1951) contributed further observational evidence in support of the concept of high and low index states of the general circulation by demonstrating that zonally averaged sea-level pressures at 35° N and 55° N show a strong negative correlation. Based on an expanded data set for monthly mean sea-level pressure, Wallace and Gutzler (1981) cited a value of −0·8, which is as strong as the strongest negative correlations in any of the regional teleconnection patterns that they found.

The papers of Rossby and Willett (1948) and Namias (1950) introduced a tentative physical interpretation of this low-frequency variability based on the notion of an "index cycle". Index-cycle fluctuations were viewed as resulting from the combined action of cyclogenesis, diabatic heating gradients and frictional dissipation. It was hypothesized that the transition from the high index to the low index state is brought about by the simultaneous amplification of extratropical cyclones in several sectors of the hemisphere, each resulting in an outflow of cold air from the polar cap region and, through the occlusion process, in the creation of cold cyclonic vortices in lower middle latitudes so that in the zonal average, the zone of strongest baroclinity is displaced far to the south of its "high index" position. Meanwhile, the enhanced equatorward flux of cyclonic vorticity associated with the development of these vortices at upper levels was thought to result in a southward displacement of the zonally-averaged jetstream. The reverse transition was attributed to the action of diabatic heating in re-establishing the high latitude baroclinity and frictional dissipation in spinning down the vortices left behind by the simultaneous baroclinic developments. The early hopes for the development of viable long-range forecasting schemes based on the zonal index never materialized for lack of strong lag-correlations between the zonal index and other atmospheric variables (e.g., see Willett (1948)). Efforts to develop such schemes were largely abandoned during the 1950s when it became evident that zonal index fluctuations defined on the basis of data in different longitudinally localized sectors of the hemisphere were not well correlated with one another (J. Namias, personal communication, 1982). However, the concept of the index cycle has recurred from time to time in the literature as a model for interpreting low-frequency fluctuations in the kinetic energy cycle (Winston and Krueger, 1961; Krueger et al., 1965; and McGuirk and Reiter, 1976).

Several aspects of the index cycle hypothesis are difficult to reconcile with observations. The notion of coordinated outbreaks of cyclogenesis on a hemispheric scale seems incompatible with the presence of the northern hemisphere winter-time stationary waves which give rise to strong longitudinal contrasts in local baroclinity along any given latitude circle. An additional factor which should tend to localize baroclinic outbreaks is the predominantly two-dimensional character of planetary wave dispersion in the northern hemisphere troposphere (Hoskins (1983), Wallace and Hsu (1983), Blackmon et al. (1984a, b)). And finally it should be noted that this interpretation does not account for Rossby's reported correlation between the longitude of the Aleutian low and the zonal circulation index.

Holopainen (1970) and Manabe and Terpstra (1974) have shown that the energetics of orographically forced planetary waves, as represented in the kinetic energy cycle of Lorenz (1955), are analogous to those of baroclinic waves. Hence, it is plausible that interactions between orographically-forced planetary waves and the mean zonal flow might be capable of modulating the energetics, on a time scale of weeks, in a manner that mimics the index cycle. Furthermore, Plumb (1983) has shown that large energy conversions in the Lorenz cycle can occur even in the absence of any dynamically significant wave/mean flow interaction. Hence, analyses of low-frequency fluctuations in terms of hemispherically integrated energy cycle statistics are not well suited for deducing cause and effect relationships. In our view, a preferable approach is to apply the simpler compositing and correlation techniques used in the earlier studies to the greatly expanded data set that has been accumulated in the decades since the work of Rossby and collaborators, including upper air data.

In the present study, we will make use of composite and correlation maps based on a number of simple circulation indices in order to document the relationship between (1) the zonal index used by Rossby and collaborators, (2) mean square eddy amplitude integrated over the full hemisphere and over the 35°–55° N latitude belt, and (3) the amplitude of the "standing mode", i.e., the mode of transient eddy variability that exhibits exactly the same spatial pattern as the climatological mean stationary waves.

If the index-cycle hypothesis is valid, then we should expect to see a rather strong negative correlation between the zonal index and eddy amplitude on time scales of week or longer and composite maps for high (low) zonal index should resemble composite maps for high (low) eddy amplitude. Furthermore, if cyclone scale waves, whose phases are presumably random with respect to longitude, are primarily responsible for the fluctuations in eddy amplitude, then composite maps based on high and low eddy amplitude should not be expected to show distinctively different wave patterns.

2. Data and analysis procedure

This study is based on operational analyses of 500 mb height and sea-level pressure by the US National Meteorological Center, archived in the NCAR Data Library.* The data set comprises 27 midwinter seasons (1948/49 through 1958/59 and 1961/62 through 1976/77) where "midwinter" is defined here as the 14 pentads extending from 12 December through 19 February. (The rather short season was used in order to minimize the contribution of the climatological mean annual cycle to the variance statistics.) The data were preprocessed by H. J. Edmon at the University of Washington to form non-overlapping 5 day means. (Edmon's data set is also archived in the standard format in the NCAR Data Library.)

Throughout this section, the time mean of a quantity x is defined as

$$\bar{x} \equiv \sum_y \sum_p x_{yp} = \sum_i x_i, \tag{1}$$

where x_i is the value of x for the ith pentad of the data set, or, alternatively, x_{yp} is the value of x in the pth pentad of the yth midwinter season.

Deviations from zonal averages, referred to as the "eddy" component of the field are defined as

$$x^* \equiv x - [x], \tag{2}$$

where the zonal average $[\ ]$ is based on grid-point data at 5° longitude intervals.

The zonal index used in this study is defined as

$$\mathrm{ZI} \equiv [p](35°\,\mathrm{N}) - [p](55°\,\mathrm{N}), \tag{3}$$

where $[p]$ is the sea-level pressure averaged around the entire latitude circles, as indicated.

* The sea-level pressure data were reanalyzed under the sponsorship of the U.S. Navy Fleet Numerical Weather Central at Monterey, California.

The eddy mean square amplitude index is defined as

$$E \equiv \langle Z^{*2} \rangle, \tag{4}$$

where Z represents 500 mb height and $\langle\ \rangle$ denotes the average over the entire polar cap region poleward of 20° N, computed by averaging values on a 5° × 5° grid, where each value is weighted by the cosine of its latitude. Values of E were computed for each of the 14 pentads in each of the 27 midwinter seasons.

Even within the short midwinter season used in the present study there is some tendency for the largest values of E to cluster toward the middle of the season when the circulation, on average, tends to be most intense. In order to eliminate such seasonal bias from our statistics we computed an eddy amplitude anomaly index

$$e_{yp} \equiv \frac{E_{yp} - \tilde{E}_p}{\tilde{E}_p}, \tag{5}$$

where $\tilde{E}_p$ is the 27 season mean for the pentad corresponding to a particular group of calendar dates (e.g., December 17–21, 22–26, 27–31, etc.). Hence, if $e > 0$, the mean square eddy amplitude is greater than the seasonally adjusted normal and vice versa; a value of $e = 0.23$ corresponds to 23% above normal.

In order to assess the eddy amplitude in the latitude belt corresponding to ZI, we computed an auxiliary index, e_{45}, defined in the same manner as e except that the integration is carried out in the 35°–55° latitude belt, rather than over the entire hemisphere.

The standing mode amplitude index is defined as

$$S \equiv \frac{\langle Z^* \bar{Z}^* \rangle}{\langle \bar{Z}^{*2} \rangle} - 1 = \frac{\langle Z'^* \bar{Z}^* \rangle}{\langle \bar{Z}^{*2} \rangle}, \tag{6}$$

where $\bar{Z}^*$ is the climatological mean stationary wave component of the 500 mb height field; and Z'^* is the transient eddy component. Formally, the first term in (6) is the normalized projection of the transient eddy component of the 500 mb height field for a particular pentad and year upon the climatological mean stationary wave component. Hence if $S > 0$, the circulation may be regarded as being characterized by an enhancement of the climatological mean stationary wave pattern and vice versa.

3. Results

Fig. 1 shows composite 1000 mb and 500 mb charts for contrasting extremes of the zonal index as defined in (3). Details of the compositing procedure are given in the figure caption. The high index composite 1000 mb height pattern is characterized by deep lows over the northern oceans, strong subtropical oceanic highs and a weak Siberian high. Strong westerly flow dominates the oceanic sectors and northern Europe and westerlies extend across the northern United States. The contrasting low-index composite is characterized by a strong Siberian high and an analogous subarctic high over the Yukon. Surface easterly flow prevails over southern Europe and most of western North America. Consistent with the results of Rossby (1939) the Aleutian low seems to be centered farther westward in the low-index composite than in the high-index composite.

The 500 mb height composites exhibit an obvious contrast in zonal wind speed in the 35°–55° N latitude belt. The phases of the planetary waves in the two composites are also quite different. The most striking contrast is in the North American sector where, along 55° N, the ridge position shifts from 125° W in the high index composite to 160° W in the low-index composite.

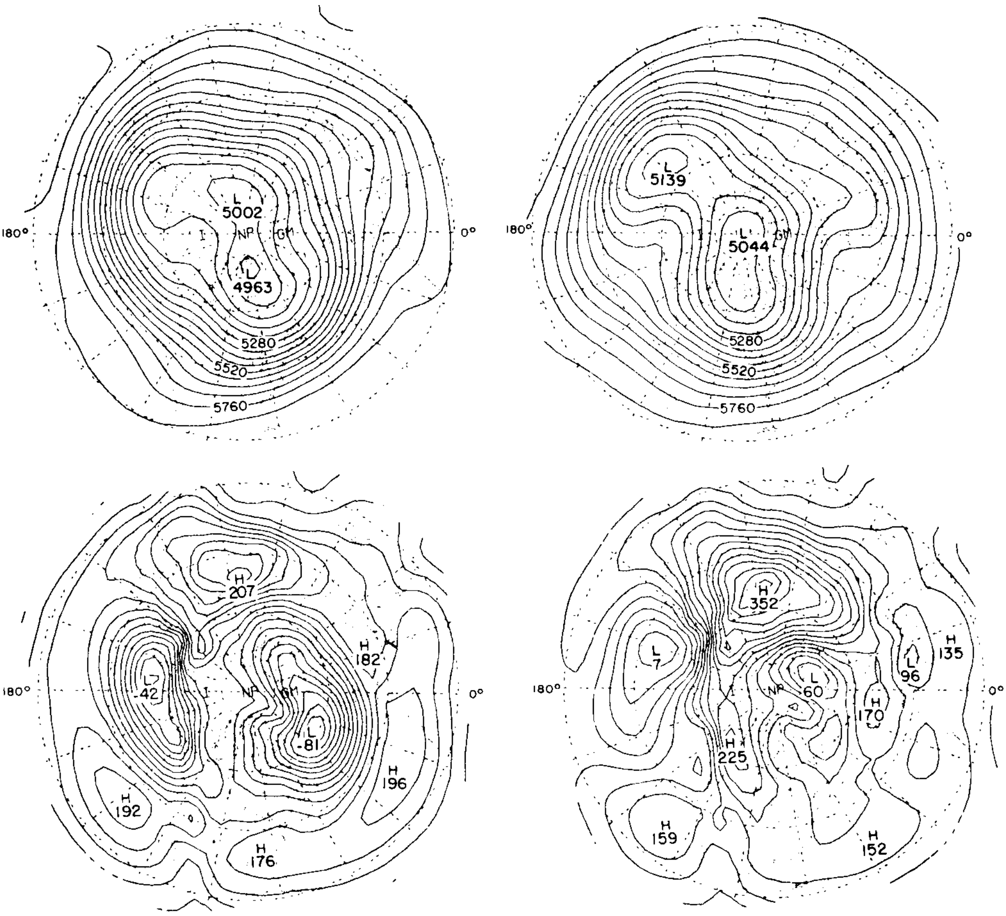

Fig. 1. Composite 500 (upper) and 1000 mb (lower) height charts corresponding to high (left) and low (right) zonal index circulations. The zonal index ZI is defined in (3). The high-index composite is based on the 26 pentads with ZI > 10.6 mb and the low-index composite is based on the 26 pentads with ZI < −3.5 mb. 1000 mb charts are based on sea-level pressure charts with isobars relabeled as height contours in units of m. The contour interval is 60 m for 500 mb height and 30 m for 1000 mb height.

There is a similar westward shift of the trough in the Black Sea/Mediterranean region from the high to the low index composite. It is interesting to note that these phase shifts are all in the sense hypothesized by Rossby (1939).

By subtracting the low-index composite 1000 mb height, 500 mb height, and 1000/500 mb thickness fields from their respective high-index counterparts, we have produced the three maps in Fig. 2. The 1000 mb composite difference field is the most zonally symmetric of the three. It shows evidence of the signatures of the north Atlantic and north Pacific oscillations described by Walker and Bliss (1932), van Loon and Rogers (1978), Rogers (1981) and Wallace and Gutzler (1981) and a third, unnamed north–south dipole pattern located near 80° E. 1000 mb height decreases poleward in the 35°–55° latitude belt at all longitudes. It seems reasonable to suppose that the strong zonal symmetry at this level is, at least in part, a consequence of the analysis scheme. On the other hand, in view of the results of Lorenz (1951), Kutzbach (1970), and Wallace and Gutzler (1981), one cannot, at this point, dismiss the possibility of a real, zonally symmetric seesaw in sea-level pressure between high and low latitudes. The 500 mb composite is similar, but the deviations from zonal symmetry are larger, as evidenced by the absence of a meridional gradient over the north American sector. To a first level of approximation, the composite 1000 and 500 mb height difference pattern shows an equivalent barotropic structure, with amplitude increasing with height. However, the corresponding thickness pattern is much less zonally symmetric. High index situations tend to be warmer over western Canada and much of the corresponding latitude belt of Asia and colder over the oceanic sectors of the hemisphere than low index situations. The contention of Willett (1948), Rossby and Willett (1948) that low index situations tend to be characterized by an expanded polar vortex with lower temperatures in middle latitudes is probably valid for the zonally averaged thickness field but such a description ignores the most striking features in the thickness field, which tend to be of a regional rather than a hemispheric scale.

Composite 500 mb height charts based on contrasting extremes of the eddy amplitude anomaly index e are shown in Fig. 3. The high index composite is characterized by a much stronger wave pattern with more involvement of the

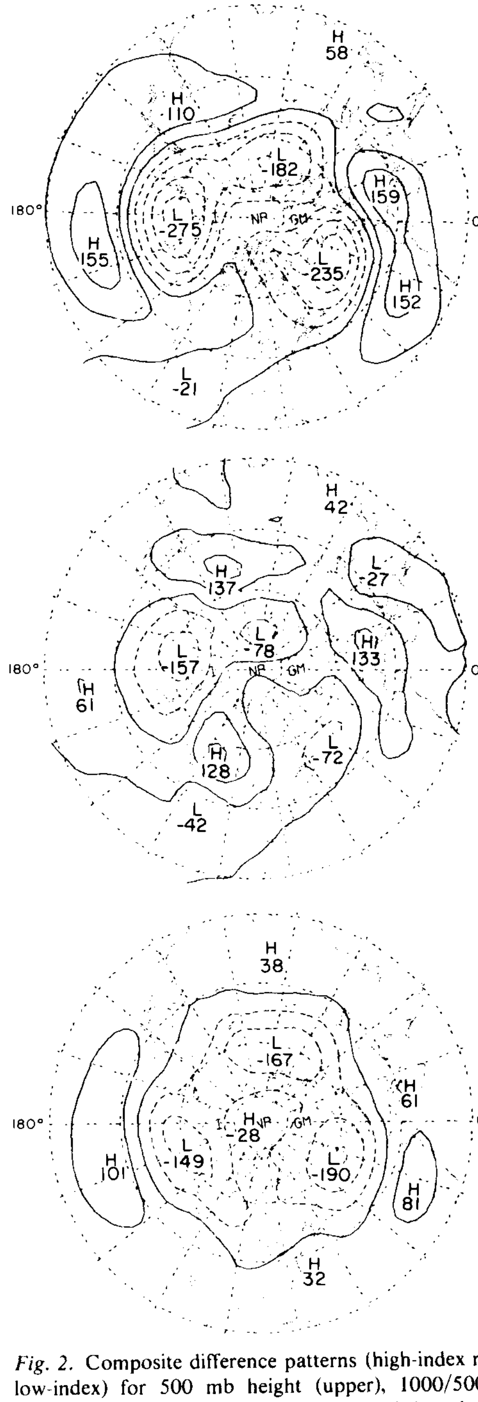

Fig. 2. Composite difference patterns (high-index minus low-index) for 500 mb height (upper), 1000/500 mb thickness (middle), 1000 mb height (lower), based on the same compositing criteria as in Fig. 1. Labels in m; contour interval 60 m.

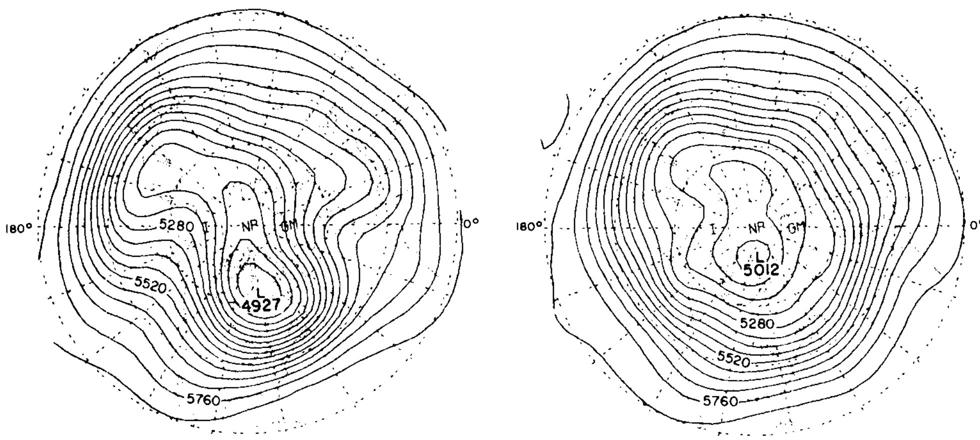

Fig. 3. Composite 500 mb height charts corresponding to high (left) and low (right) eddy amplitude anomaly index situations. The index e is defined in (5). The high-index composite is based on the 29 pentads with $e > 0.16$ and the low-index composite is based on the 29 pentads with $e < -0.16$. Labels in m; contour interval 60 m.

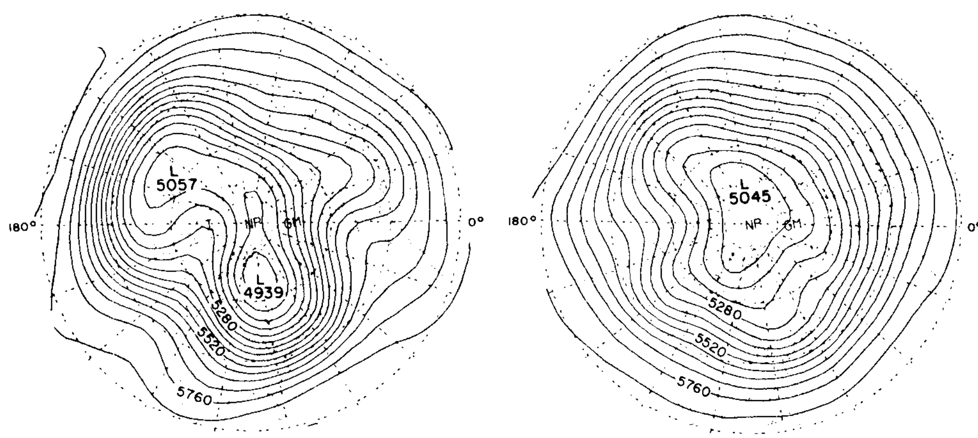

Fig. 4. Composite 500 mb height charts corresponding to high (left) and low (right) standing mode amplitude index situations. The index S is defined in (6). The high-index composite is based on the 27 pentads with $S > 0.36$ and the low-index composite is based on the 24 pentads with $S < -0.43$ Labels in m; contour interval 60 m.

ultra-long waves. It should be emphasized that this result is not a direct consequence of the compositing procedure. For example, if the fluctuations in the eddy amplitude index were reflecting a low-frequency modulation in the level of baroclinic wave activity, as in the index cycle hypothesis, the high and low index composites would be quite similar, since the phases of the waves during individual pentads should be more or less random. Evidently, this is not the case. Similar results were obtained for the index e_{45} (not shown).

Corresponding results for the standing mode index are shown in Fig. 4. The high index composite, in this case, necessarily shows a caricature of the climatological mean features while the low index pattern shows indications of only the strongest features in the stationary-wave pattern; i.e., the troughs along the east coasts of the continents. It is interesting to note that even in the extreme low-index cases the standing mode index S remains well above a value of -1.0. Hence, the stationary waves are always evident, at least to some degree in wintertime circulation patterns.

Perhaps the most important relationship implicit in Figs. 1–4 is the fact that the composite 500 mb height charts based on eddy amplitude (Fig. 3)

Table 1. *Matrix of temporal correlation coefficients between the zonal index ZI, the eddy amplitude anomaly indices, e and e_{45}, and the standing wave amplitude index, based on 5-day mean data for 27 winters*

	e	e_{45}	S
ZI	−0.27	−0.15	0.07
e		0.78	0.64
e_{45}			0.68

much more closely resemble those for standing mode amplitude (Fig. 4) than those based on zonal index (Fig. 1). The same is true for the corresponding 1000 mb height charts (not shown). It follows that:

(1) variations in the zonal index are not accompanied by major changes in the overall level of eddy activity, and
(2) variations in the amplitude of the standing mode account for much of the observed week-to-week variability in the overall level of eddy activity.

Further evidence in support of these conclusions is given in Table 1, which shows that temporal fluctuations in the overall level of eddy activity are much more strongly correlated with those in standing mode amplitude than those in zonal index. The correlation between e and S is 0.64, which indicates that variations in standing mode amplitude account for roughly half the temporal variance of low-frequency eddy activity during the northern hemisphere winter. (Wallace and Blackmon (1983) reported a similar estimate, based on a different form of analysis.) The correlation between e and ZI (−0.27) indicates that fluctuations consistent with the index cycle model envisioned by Rossby and collaborators account for less than 10% of the variance of the zonal index or of the amplitude of the eddies. The more local eddy amplitude index e_{45} is even more strongly correlated with S, and less strongly correlated with ZI.

It is conceivable that, despite the rather weak temporal correlations between ZI and e, a stronger inverse relation might exist within some range of frequencies. In order to investigate this possibility, we performed cross spectrum analysis between ZI and e and examined the coherences and phases. The spectra for the two time sereis were found to be comparably "red" and neither showed evidence of significant peaks. An out of phase relationship was observed at all periods between 10 and 60 days, but the coherence squares were found to be uniformly low (near or below 0.10). Hence it appears that the relationship between e and ZI is indeed a rather weak one at all frequencies.

4. Discussion

Our results support the view espoused by Rossby (1939) that low-frequency fluctuations in the zonally averaged circulation are accompanied by shifts in the phases of the forced, quasi-stationary planetary waves: in agreement with their results, we find that a number of prominent planetary-wave features tend to be located farther toward the east during high zonal index situations than during low zonal index situations. On the other hand, the absence of zonal symmetry in the corresponding temperature fluctuations (Fig. 2, middle panel), and the lack of strong negative correlation between the zonal index and the eddy amplitude index (Table 1) all argue against the "index cycle" hypothesis proposed by Rossby and Willett (1948) and Namias (1950) or amplitude vacillation of baroclinic waves as a major cause of low-frequency variability of the Northern Hemisphere wintertime circulation. The results of Lorenz (1951) notwithstanding, it is still possible that the observed low-frequency fluctuations in the zonal index may be nothing more than a collection of unrelated signals associated with regional phenomena, such as blocking and two dimensional barotropic instability, whose signatures do not completely cancel in zonal averages. Therefore it is not clear that an alternative mechanistic explanation of these fluctuations is really necessary. It may be more fruitful at this point to resume the line of investigation begun by Rossby (1939), which was directed toward an understanding of the relationship between the zonally averaged flow and the stationary wave pattern. A recent example is the work of Branstator (1984) who has been able to simulate some of the observed wave/zonal flow relationships at the 300 mb level using a linearized model based upon the barotropic vorticity equation.

In the view of the widespread use of diagnostics based on Lorenz's (1955) formulation of the kinetic energy cycle in studies of low-frequency atmospheric variability (e.g., see Krueger *et al.*, 1965; McGuirk and Reiter, 1976), the strong positive correlation between our eddy emplitude index E and standing mode amplitude index S is of interest since it indicates that variance statistics such as hemispherically averaged available potential energy and kinetic energy are extremely sensitive to fluctuations in the standing mode. To illustrate why this sensitivity arises we may express the transient eddy component of the geopotential height field as

$$Z'^{*} = S\bar{Z}^{*} + \hat{Z} \tag{7}$$

where S is defined in (6) and $\hat{Z}$ is linearly independent of $\bar{Z}^{*}$ so that

$$\langle \bar{Z}^{*}\hat{Z} \rangle = 0. \tag{8}$$

The hemispherically averaged, spatial variance of the transient eddies is given by

$$E \equiv \langle Z^{*2} \rangle = \langle (\bar{Z}^{*} + Z'^{*})^{2} \rangle . \tag{9}$$

Using (7) and (8), it can be rewritten in the form

$$E = (1 + 2S)\langle \bar{Z}^{*2} \rangle + S^{2}\langle \bar{Z}^{*2} \rangle + \langle \hat{Z}^{2} \rangle. \tag{10}$$

The first term on the right-hand side of (10) is a constant, the second involves the projection of Z'^{*} field upon the stationary wave pattern, the third depends upon the amplitude of the standing mode and the fourth upon the amplitude of modes of variability of the Z'^{*} field that are spatially orthogonal to the standing mode. Of the four terms, the second term alone is responsible for the linear temporal correlation between E and S and the similarity between Figs. 3 and 4. From (10) it is evident that the peculiar leverage of the standing mode in the energetics does not stem from its importance as a mode of variability in the Z'^{*} field. The standing mode does not, in fact, emerge as the leading mode in an EOF expansion of the Z^{*} field (Branstator, 1984), and even if it did, the second (linear) term on the right-hand side of (10) would not be important if the climatological mean stationary waves did not have appreciable amplitudes in comparison to the transient eddies. The relative magnitude of the second and third terms on the right-hand side of (10) depends upon the typical magnitude of S, which can be estimated by evaluating $(S'^{2})^{1/2}$ from the observations, which works out to a value of 0.26. It follows that the linear term $2S\langle \bar{Z}^{*2} \rangle$ is eight times as large as the quadratic term $S^{2}\langle \bar{Z}^{*2} \rangle$. In other words, the standing mode contributes eight times as much to the temporal variance of E as a mode of identical shape and amplitude would contribute in the absence of the climatological mean stationary waves.

The corresponding standing mode in the southern hemisphere should have much less leverage in the energetics because the stationary waves are much weaker there. Hence it seems likely that vacillation phenomena, involving interactions between the zonal flow and the transient eddies might play a more prominent role in the southern hemisphere general circulation. Webster and Keller (1975) have shown evidence of fluctuations in the southern hemisphere zonal mean flow, with periods around three weeks, which involve barotropic energy exchanges with the eddies. There is also evidence that pure zonal harmonics play a prominent rôle in the low-frequency eddy fluctuations in the southern hemisphere [Mo and White (1985)], in contrast to the northern hemisphere, where more regional patterns prevail (Wallace and Hsu, 1983).

For the synoptician, there is a certain familiarity about the contrasting circulations for the "high and low index" states over certain sectors of the hemisphere. These contrasts were brought out even more sharply in some of the early work (e.g., see Starr (1942) or Willett (1944)) based on partial zonal indices. For example, the "low index state" with the cold, continental anticyclone to the lee of the Canadian Rockies and the easterly, upslope flow over the northern US Great Plains is one of the recurrent patterns in the synoptic climatology of North America. These patterns and their associated anomaly fields are highly baroclinic, and they appear to be associated with the major mountain ranges. We have recently completed a more detailed study of these patterns, using analysis techniques more suitable for focusing on regional scale features (Hsu and Wallace, 1985).

Finally, it should be noted that the circulation features which appear in composite or correlation maps based on zonal indices depend upon the choice of latitude belts for which the pressure gradient is computed. Separate analyses were carried out based on sea-level pressure differences across the 25°–45° N latitude belt and across the 45°–65° belts. Results of the former (not shown) are qualitatively similar to those presented in this paper, although the contrasts between the high- and low-zonal index composites are less pronounced. As in Figs. 1 and 2, the prominent ridges and troughs tend to be located farther eastward in the high-index composite than in the low index composite. Results for the 45°–65° latitude belt are less interesting, with marked contrasts between high and low-index composites confined to high latitudes and to the Atlantic sector.

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