Reply

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We thank Dr. Robinson for his comments (Robinson 2004). Robinson argues that the results of Cash et al. (2002, hereafter CKV) are not inconsistent with the presence of an annular mode (AM) in the numerical model used. He suggests that the zonally asymmetric character of CKV's AM events is due to the superposition of independent annular and nonannular features, with AMs being (presumably) a real dynamical phenomenon independent of the zonally asymmetric eddying motion. However, while it may be impossible to rule out the presence of such an AM in the CKV experiments, we do not believe that the AMs, thus interpreted, necessarily best represent the underlying dynamical behavior of the model.

The AM problem has descriptive aspects and dynamical aspects. In CKV, we look for useful statistical descriptions of the spatial structure of extratropical atmospheric low-frequency variability in an aquaplanet model. We calculate the leading EOF of the hemispheric-wide surface pressure and the leading EOF of the zonal-mean surface pressure. We find that these two structures have practically identical *meridional* structures (Fig. 1); that is, the zonal mean of the hemispheric-wide surface pressure EOF is the same as the EOF of the zonal-mean surface pressure.

The meridional structure of the AMs is similar to the zonal mean of circulation anomalies in smaller zonal sectors. One way of seeing this is to calculate the leading EOF of the surface pressure in a 90° longitude sector (CKV, Fig. 11). The zonal mean of this structure, shown as a dotted line in Fig. 1, is also very similar to the other two curves in the figure. Another way to obtain maps of characteristic localized circulation anomalies is to calculate the teleconnection patterns in the surface pressure. These are structures with a characteristic longitudinal scale of about 90°. As can be inferred from CKV (their Figs. 9a,b), these also have an AM-like meridional structure, with maxima and nodes appearing at similar locations to those in Fig. 1. Thus, the meridional structure seen in the zonal-mean AMs is quite robust and appears using several different analysis techniques.

The meridional dipole structure in Fig. 1 is characteristic of the zonal-mean anomalous circulation on various time scales. It can be seen in snapshots of the zonal-mean flow as well as in long-term composites over high- or low-AM index periods (not shown). This is because it is related to the position of the model's zonal-mean circulation; for example, when the model's AM index is positive, the zonal-mean circulation is shifted pole-

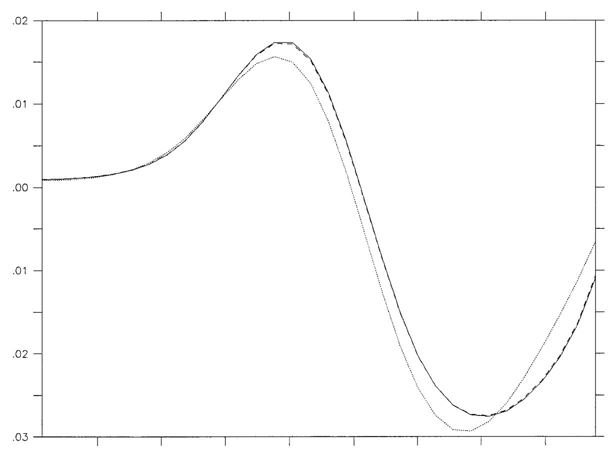

FIG. 1. EOF of the zonal-mean surface pressure in the CKV model (solid), zonal mean of the nonzonally averaged surface pressure in the CKV model (dashed), and zonal mean of the sector EOF shown in CKV's Fig. 11a (dotted–dashed).

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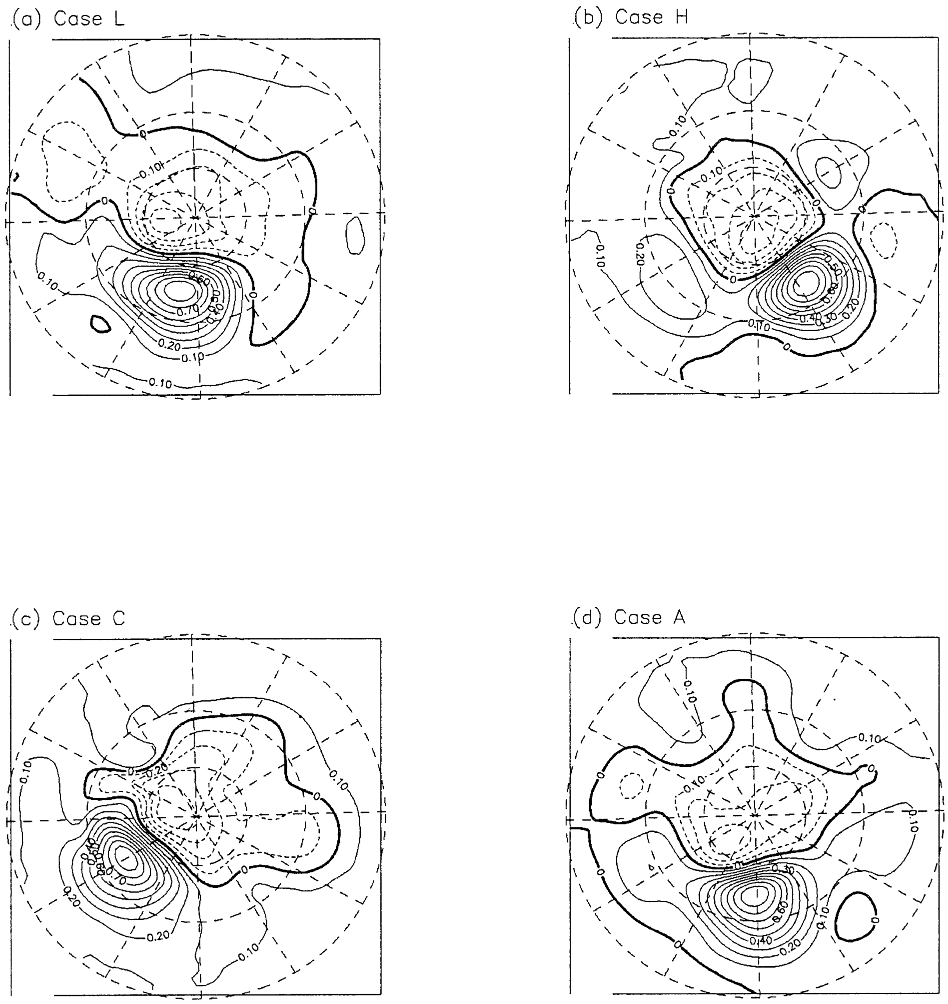

Fig. 2. Surface pressure teleconnection patterns for (a) case L, an integration in which the model has a strong land–sea contrast and a flat lower boundary; (b) case H, with moderate land–sea contrast and moderate topographic forcing; (c) case C, with strong land–sea contrast and strong topographic forcing; and (d) case A, the aquaplanet model of CKV. Contours denote one-point correlation maps. Contour interval is 0.1, and dashed contours are negative (Cash et al. 2003, manuscript submitted to *J. Atmos. Sci.*)

ward. We conclude that the meridional structure of the hemispheric-wide EOF—that is, of the AM—is both robust and representative of typical zonal-mean circulation anomalies.

This conclusion does not extend to the *two-dimensional* structure of the AM. This structure is too zonally symmetric to well represent the two-dimensional flow on high- and low-AM index days. That is, in our model (CKV, their Fig. 7), the hemispheric-wide AM structure is not typically seen in snapshots of the low-pass-filtered data. Furthermore, the zonal structure does not survive in the teleconnection plot (CKV, their Figs. 9a,b) or in the sector EOF (CKV, their Fig. 11; Ambaum et al. 2001). The teleconnection and the sector EOF, on the other hand, do have a similar localized zonal structure. We notice that, in Robinson's model (his Fig. 1), more zonal structures are present on high-index days, indicating that the eddy activity in his model is relatively weak. In general, however, the latitude–longitude map of the AM, at least in the lower troposphere, is not representative of the latitude–longitude flow patterns, and is therefore, perhaps, not a useful description of the low-frequency variability.

The sector EOF and the zonally localized teleconnection patterns may provide a more useful description of the two-dimensional structure for two reasons. First, these patterns, with their characteristic northwest–southeast phase tilt, can be seen in typical snapshots of the two-dimensional flow (CKV, Fig. 7). These patterns represent the typical zonally localized flow pattern that one would find on a given day in which the zonal-mean flow is in a high- or low-AM index state. Second, we find that the zonally localized structures are not unique to the zonally homogeneous CKV model. In Fig. 2, for example, we show the teleconnection patterns from three models that are strongly zonally inhomogeneous, because of land–sea contrasts and topographic forcing,

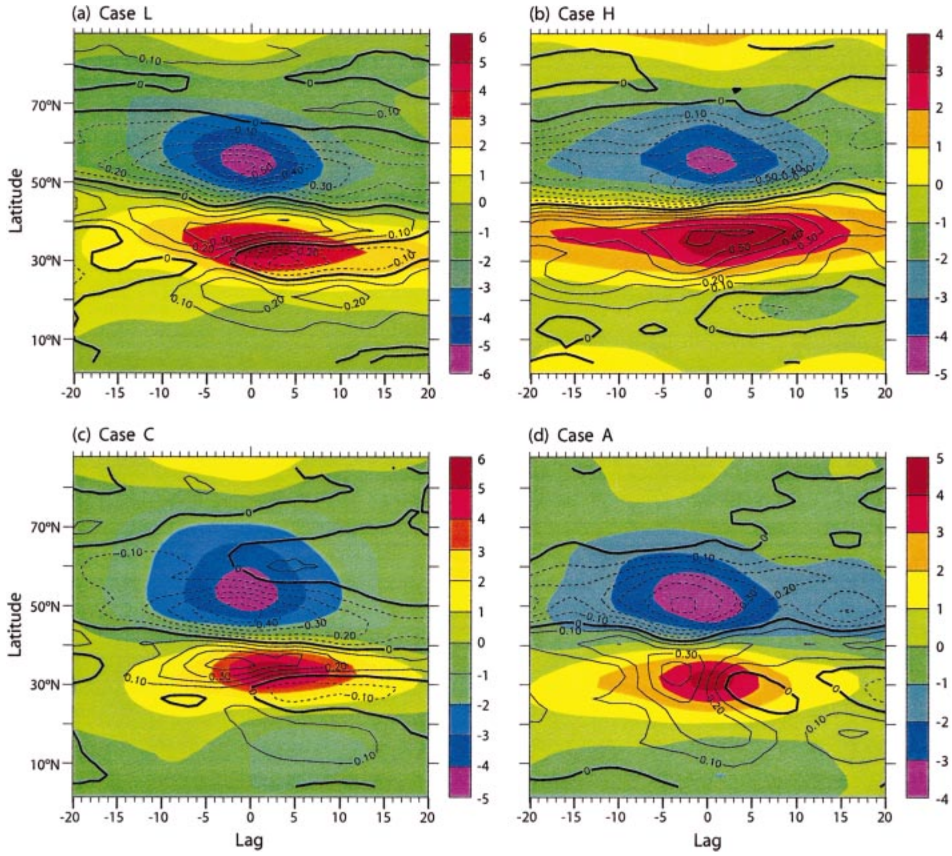

FIG. 3. As in Fig. 2, for the regressed zonally averaged zonal wind anomalies (shading) and anomalous eddy momentum flux convergences (contours). Units of wind are m s^{-1}; units of momentum-flux convergences are m s^{-1} day^{-1}.

as well as from the zonally homogeneous aquaplanet model (Cash et al. 2003, manuscript submitted to *J. Atmos. Sci.*). It can be seen that these structures are very similar among the various simulations, despite the wide variation in lower boundary conditions for these models.

Regarding the dynamical aspects of the AM problem, we agree with Robinson that only a fuller appreciation of the dynamics will lead to a better understanding of low-frequency variability of the extratropical general circulation and the relevance of AMs. Our current understanding is that much of this variability is forced by high-frequency transient eddies, consistent with Robinson's Fig. 3. Our analysis shows that, at least within our models, the high-frequency eddy forcing gives rise to zonally localized circulation anomalies, whose structures are seen in the sector EOF or the teleconnection patterns, and that, as we have said, project onto the zonal mean (Fig. 3). Focusing on these regional patterns has led to insights into the problem in zonally inhomogeneous models and in the observations. These ideas are discussed further in two forthcoming studies (Vallis et al. 2004; Cash et al. 2003, manuscript submitted to *J. Atmos. Sci.*).

We conclude, then, that the two-dimensional, hemispheric-wide AM is not a particularly illuminating way to represent the underlying dynamics. Such a structure arises from the EOF analysis and is not a dominant feature of the flow itself. Our understanding of zonal-mean AM dynamics could therefore, we believe, be improved by focusing on the local circulation anomalies associated with zonal-mean AM events.

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