

Atmospheric teleconnections, forced planetary waves and blocking

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A brief review is given of some recent observational and theoretical advances in our understanding of the role of the steady, forced, planetary waves in determining anomalies from mean tropospheric conditions. Observational evidence of planetary-scale, horizontal teleconnections in the troposphere and their relationship to blocking episodes in the northern hemisphere is presented.

Anomaly patterns similar to some of the observed teleconnections are found in linear, steady-state solutions of numerical models with large-scale thermal or orographic forcing. For appropriate relative positions of the thermal and orographic forcing, the model response east of the forcing may resemble an incipient blocking situation. The wave train pattern of anomalies can be interpreted using simple wave theory as essentially the result of the propagation of stationary, barotropic Rossby waves away from the forcing.

Introduction

Atmospheric blocking, as discussed and defined in earlier papers, is a major cause of anomalies from the mean climate on time-scales of a week to a season.

The relationship between such climatic anomalies in one region and those in other regions at large distances was the subject of an exhaustive study by Walker and Bliss (1937 and references). They calculated temporal correlations of surface pressure, temperature and rainfall between different places in the world and found three major patterns, which they termed the North Atlantic, the North Pacific and the Southern Oscillations. These were the first detailed descriptions of what are commonly called teleconnections in the atmosphere. They can be defined as significant simultaneous correlations between the temporal fluctuations of meteorological parameters at widely separated points on the earth.

There has been continuing interest in the study of teleconnections as a measure of the global-scale variability of the atmosphere, as an indicator of possible oscillations of the standing wave pattern and, not the least, as an aid to long-range forecasting. A comprehensive review of the literature on observational studies of teleconnections has been given recently by Wallace and Gutzler (1981; hereafter referred to as WG), who describe recurrent spatial patterns of monthly mean anomaly fields at the surface and in the middle troposphere. In the following section, we concentrate on the observational evidence for one teleconnection pattern studied by WG, which is associated with blocking over North America.

Few theoretical studies have been aimed directly

at studying teleconnections; however many more have attempted to explain the forcing and variability of standing waves in the atmosphere. Charney and Eliassen (1949) and Smagorinsky (1953) gave the first detailed accounts of the standing wave response to large-scale orographic and thermal forcing in the atmosphere, using linear β -plane models. Subsequently there have been numerous papers published on the response to these two forcings but only a few gave results which resembled the observed teleconnections.

The general circulation model studies of the response to subtropical sea surface temperature anomalies by Rowntree (1976) and others showed large, middle and high latitude perturbations which were similar to some of the observed teleconnections. More recently, Opsteegh and van den Dool (1980), Hoskins and Karoly (1981) and Webster (1981) have used linear baroclinic models to study the steady response to sea surface temperature anomalies. They all found that low latitude forcing gave a large amplitude wave train response at middle and high latitudes which resembled the observed teleconnections. Hoskins and Karoly showed that orographic forcing also produced a wave train response at high latitudes and they used simple wave theory to explain this response.

Some of the results of Hoskins and Karoly (1981; hereafter referred to as HK) for the steady, linear response of a numerical model to large-scale thermal and orographic forcing are presented later in this paper. A possible relationship with blocking episodes is discussed. A brief outline of the interpretation of the model results and the observed teleconnections using simple wave theory, as described in HK, is given in a later section.

The focus for this paper is the relationship

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between atmospheric teleconnections, forced planetary waves and blocking. More general reviews of observational and theoretical studies of stationary and quasi-stationary eddies in the extratropical troposphere and their interaction with the tropics are given in the recent collection of papers edited by Hoskins and Pearce (1982) and readers are referred to that for general background and further details. More general reviews of atmospheric blocking and descriptions of other possible mechanisms for the generation and maintenance of blocking are presented in the other papers in this issue.

Observations

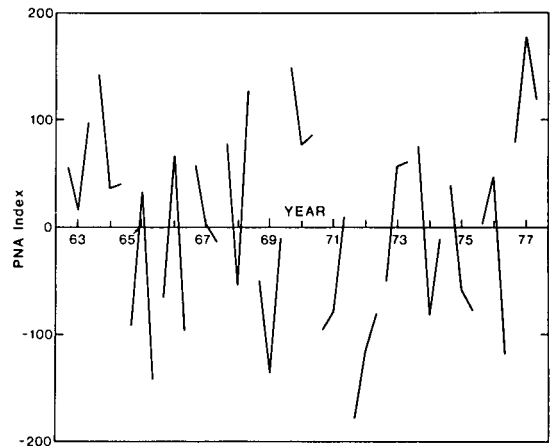
With the increasing availability of long time-series of global data, there recently has been a number of observational studies of the spatial variability of monthly mean surface pressure and geopotential height. These studies generally have concentrated on the middle and high latitude northern hemisphere as the data coverage and availability are best in this region.

In the northern hemisphere winter, two different types of teleconnections of geopotential height have been identified by WG. These can be described as:

- (a) a zonally symmetric, global-scale 'see-saw' between polar and temperate latitudes, which is most apparent in the surface pressure field; and
- (b) patterns of a more regional scale which are characterised by an equivalent barotropic vertical structure and are more clearly defined at mid-tropospheric levels than at the surface. Their horizontal structure in the middle troposphere tends to be wavelike with multiple centres of action. These patterns are indicative of standing oscillations in the planetary waves with time-scales of one month or longer.

Here, we concentrate on the teleconnection which is most apparent in time series of monthly mean geopotential height anomalies in the northern hemisphere middle troposphere during winter. This has been called the Pacific North American (PNA) pattern by WG and is characterised by positive height anomalies over Hawaii and western Canada and negative anomalies over the North Pacific Ocean and southeastern United States. The time series of an index based on this pattern has been given by WG and is shown in Fig. 1. Months with large positive values of the index have height anomalies as described above and months with large negative values of the index have anomalies of the opposite sign. The composite 500 mb height field based on the 10 months (of the 45 winter months available) with the largest positive values of the PNA index is shown in Fig. 2(a). This has an amplified meridional structure with a ridge over western Canada and a trough over the eastern United States which is typical of blocking over

Fig. 1 Time series of the Pacific North American (PNA) pattern index for the three winter months of the 15 winters from 1962-63 to 1976-77. The index is a measure of the amplitude of the PNA teleconnection and is defined in Wallace and Gutzler (1981).



western North America. Examples of this pattern occurred in the eastern United States in the severe winters of 1962-63 and 1976-77, when the PNA pattern existed from November until February. The 500 mb height anomalies typical of the PNA pattern are shown in Fig. 2(b), which is the difference of the 500 mb height between the 10 months with the largest positive values of the PNA index and the 10 months with largest negative values. The corresponding sea-level pressure anomaly pattern in Fig. 2(c) has smaller amplitude than the height anomalies but there is little tilt with height.

A simultaneous study by Horel and Wallace (1981) of atmospheric phenomena associated with the Southern Oscillation established a link between the PNA pattern and anomalies in the tropics. They found that periods of positive sea surface temperature anomalies in the equatorial central Pacific are positively correlated with anomalous high rainfall at stations in the equatorial Pacific; with negative anomalies of a Southern Oscillation index (defined as the difference between the normalised sea level pressure anomalies at Tahiti and Darwin); and with positive anomalies of 200 mb height in the tropics.

To determine any teleconnections with middle latitudes, time series of all these tropical parameters were correlated with the winter mean northern hemisphere 700 mb height. A typical correlation map is shown in Fig. 3, which is the correlation between the equatorial Pacific sea surface temperature anomaly index and the 700 mb height. The other correlation maps are similar, indicating that conditions in the tropics associated with warm sea surface temperature in the equatorial Pacific are accompanied by negative 700 mb height anomalies over Siberia and the North Pacific, positive anomalies over western Canada and negative anomalies over southeastern United States. The

Fig. 2 (a) Composite northern hemisphere 500 mb height field based on the 10 months (of the 45 winter months available) with the largest positive values of the PNA index. The contour interval is 12 dam. Lines of latitude and longitude are at 20° intervals with the outer latitude circle at 20°N. (b) Difference of the 500 mb height between the 10 months with largest positive values of the PNA index and the 10 months with largest negative values. Contour interval is 4 dam and negative values are hatched. (c) As in (b) but for sea level pressure with contour interval of 4 mb (after Wallace and Gutzler 1981).

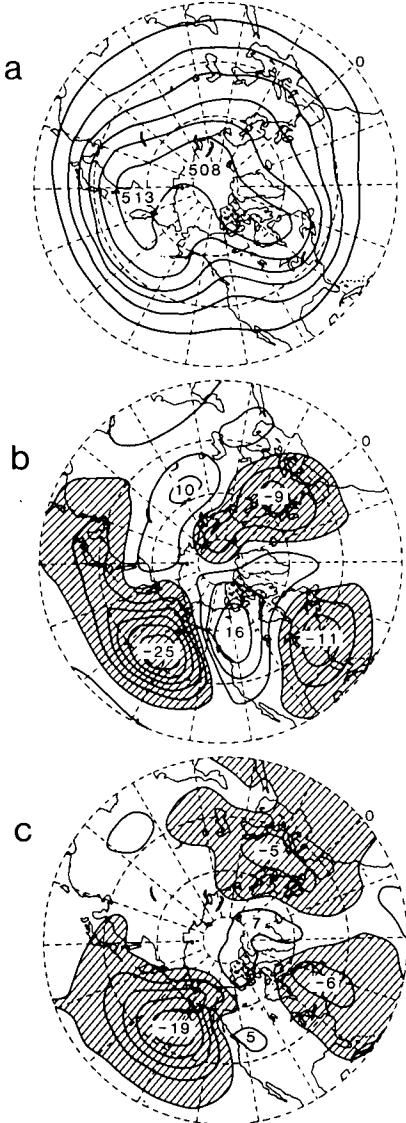


Fig. 3 Correlation coefficients between 700 mb height at grid-points poleward of 20°N and the equatorial Pacific sea surface temperature anomaly index. Contour interval 0.2 with negative values hatched (after Horel and Wallace 1981).

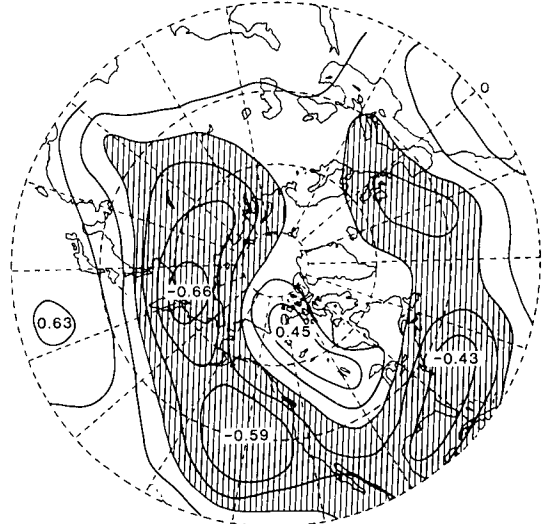


Fig. 4 The hypothesised global pattern of mid-tropospheric height anomalies (solid lines) during a northern hemisphere winter in which the equatorial Pacific sea surface temperature is above average. The arrows depict a streamline distorted by the normaly pattern. Shading indicates regions of enhanced rainfall (after Horel and Wallace 1981).

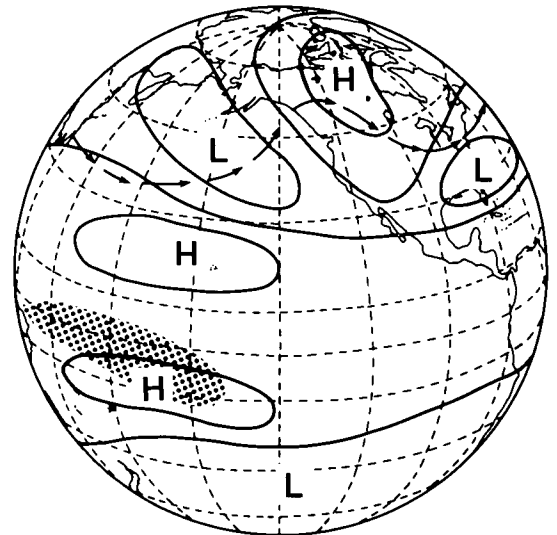
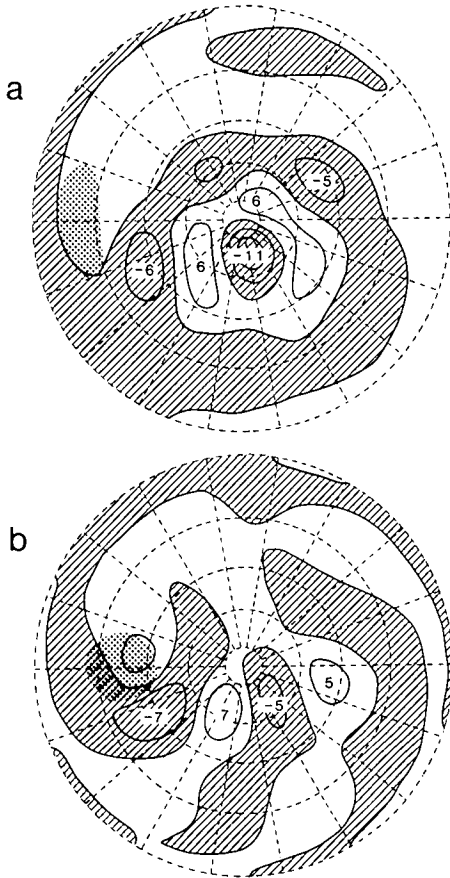


Fig. 4, illustrates the hypothesised teleconnection in the upper troposphere during a northern hemisphere winter in which the sea surface temperature is above average throughout the central equatorial Pacific. The middle latitude pattern is based on the height anomalies associated with positive PNA index, as in Fig. 2(a) and Fig. 3. The shading represents regions of enhanced precipitation, based on the results of Horel and Wallace (1981).

correlation patterns are similar to the PNA pattern and all the tropical parameters are correlated with the PNA index. This suggests that the height anomalies of the PNA pattern are related to anomalous tropical forcing.

A scenario of this type of relationship, shown in

Fig. 5 300 mb height perturbations in the linear, steady-state solutions of a numerical model with northern hemisphere winter basic state to (a) mid-tropospheric, subtropical thermal forcing, with the region of heating larger than 0.5 K day^{-1} indicated by shading, and (b) orographic forcing by a circular mountain at 30° , with the region higher than 500 m indicated by shading. The contour interval is 4 dam and negative values are hatched. Lines of latitude and longitude at 20° intervals with the outer latitude circle at the equator (after Hoskins and Karoly 1981).



Model results

Concurrent with these observational studies were several related modelling studies of the response of the atmosphere to anomalous forcing. The results from one of these, presented by HK, are described here.

Motivated by the results of Grose and Hoskins (1979) from a study of steady, linear Rossby waves forced by simple mountains in a barotropic model, a linearised, steady-state, 5-level, hemispheric, primitive equation numerical model was used to study the response of the atmosphere to orographic and thermal forcing. The climatological zonal mean northern hemisphere winter flow from Oort and Rasmusson (1971) was used as the basic state. The first case considered was for isolated mid-

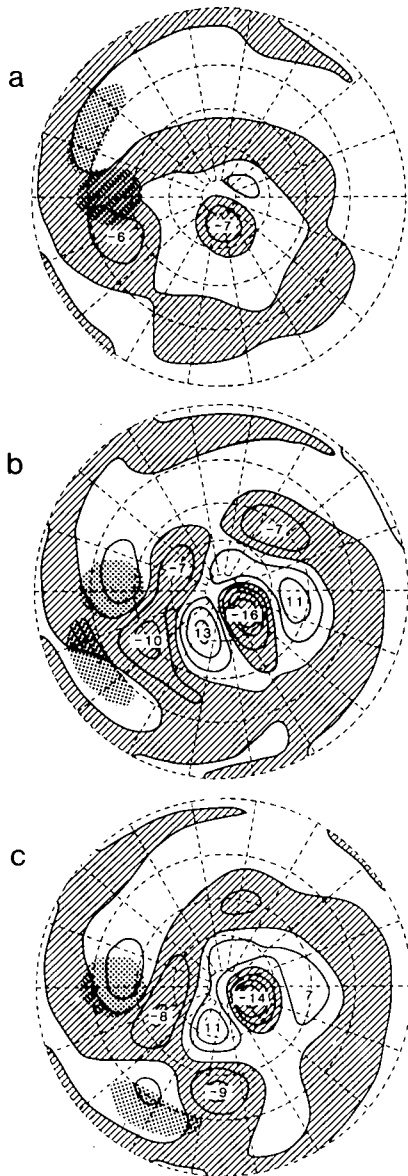
tropospheric thermal forcing in the subtropics, centred at 15° with zonal extent of 64° longitude and meridional extent of 16° latitude. Since the model was linear, the amplitude of the forcing was required only to give ideas on the magnitude of the response. For this purpose, the maximum vertically averaged heating was taken to be 2.5 K day^{-1} , which is about equal to the latent heat release of an extra 10 mm precipitation per day. The low level perturbations in the solution were confined mostly to the region of heating, but a wave train pattern of perturbations formed in the upper troposphere. This is shown by the 300 mb height perturbations in Fig. 5(a), which have maximum high of 6 dam, 60° longitude east of the heating at 60° latitude, and a maximum low of 11 dam, 110° east at 70° latitude. These perturbations have an equivalent barotropic structure, with the same sign throughout the depth and with the largest amplitude in the upper troposphere. The solution in the upper troposphere closely resembles the PNA pattern of anomalies and supports the hypothesis that anomalous tropical forcing may be a cause of the PNA teleconnection.

Thermal forcing at other latitudes was considered. For forcing at the equator, the basic state zonal wind was easterly and the wave train response in the solution was very small. Higher latitude forcing gave similar wave trains to the subtropical forcing but with smaller amplitudes. HK concluded that, for their model, it is easier to force a height anomaly of given amplitude in middle and high latitudes with a heating anomaly in the subtropics than it is with one in middle and high latitudes.

Orographic forcing in the northern hemisphere winter flow was then considered. The forcing was a circular mountain centred at 30° , of radius 45° and with height 2 km. Again the low level perturbations were confined to the region of the forcing and the interesting hemispheric patterns had large amplitude in the middle and upper troposphere. The 300 mb height perturbations, in Fig. 5(b), show a wave train pattern of anomalies with maximum high of 7 dam, 65° east of the mountain at 65° latitude, which is of the same order of magnitude as for the thermal forcing. About 80° east of the mountain, positive height perturbations are located poleward of negative perturbations in a situation which resembles a weak blocking pattern. The perturbation pattern in Fig. 5(b) is similar to that for the thermal forcing and to the PNA pattern, suggesting that an anomalous standing wave response to flow over the Tibetan plateau might play a role in generating the PNA pattern.

Concurrent with the above study by HK, two papers by Opsteegh and van den Dool (1980) and Webster (1981) appeared on similar studies of the steady atmospheric response to sea surface temperature anomalies using two-level linear numerical models. The results were similar to those in HK, showing perturbation wave trains in the

Fig. 6 300 mb height perturbations in the model solutions for combined thermal and orographic forcing. (a) Thermal forcing centred 30° longitude west of the mountain, (b) thermal forcing 30° east of the mountain, and (c) thermal forcing 60° east of the mountain. The forcing regions are indicated by shading and the contours are as in Fig. 5.



upper troposphere forced by anomalous heating. They again demonstrated the importance of subtropical forcing in regions of westerly wind for the response in middle latitudes.

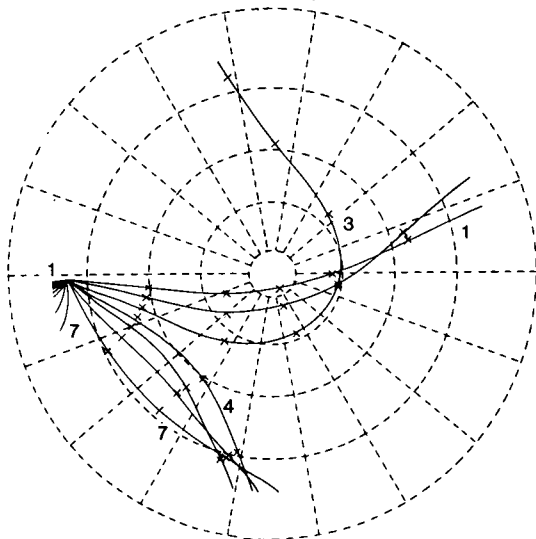
Since the model used by HK was linear, the response to combinations of thermal and orographic forcing at different positions can be found by addition of the solutions for each forcing. Several responses for combined forcing by the subtropical

heating and the mountain at 30° are shown in Fig. 6. For the heating located 30° west of the mountain, the 300 mb height perturbations in Fig. 6(a) have smaller amplitude than for either forcing alone because there is destructive interference in the combination of the two wave train responses. For the heating located 30° east of the mountain, the height perturbations in Fig. 6(b) are larger than for either forcing because there is reinforcement of the two wave train responses. The largest perturbation is a low of 16 dam at 70° latitude, 110° longitude east of the heating. When the heating is located 60° east of the mountain, the 300 mb height perturbations in Fig. 6(c) have a slightly different pattern. The high latitude wave train still exists, with maximum low of 14 dam, but there are larger amplitude perturbations in middle latitudes. About 30° east of the heating, there is a high of 11 dam polewards of a low of 9 dam, which is typical of a strong blocking pattern in the upper troposphere. This shows that the response to combined thermal and orographic forcing is dependent on the relative positions of the forcings and, for appropriate positions, may resemble a blocking situation.

Wave theory

A possible explanation for the wave train anomaly patterns found in the observational and modelling studies can be obtained from a simple analytical study of the horizontal propagation of forced, stationary Rossby waves on the sphere. HK applied

Fig. 7 Stationary wave rays for integer zonal wave numbers 1 to 7 for forcing at 15° in the northern hemisphere winter 300 mb flow. Some of the zonal wave numbers associated with the rays are shown. The crosses mark points at 180° phase separation along each ray, so that if there is a negative amplitude extreme at the source, the crosses mark the positions of successive positive and negative extremes. Lines of latitude and longitude as in Fig. 5 (after Hoskins and Karoly 1981).



kinematic wave theory to WKB wave solutions of the linearised barotropic vorticity equation on the sphere. Expressions for the group velocity and wave number were used to obtain the wave rays, which show the directions of wave propagation, and the variation of the wave amplitude and phase. The wave rays for integer zonal wave numbers 1 to 7 from a subtropical stationary wave source in the northern hemisphere winter 300 mb flow from the model basic state are shown in Fig. 7. The positions of the amplitude extremes, marked by crosses, agree well with those of the height perturbations in the upper troposphere for the subtropical thermal forcing in Fig. 5(a) and with the PNA anomaly pattern.

This simple analysis is able to describe some important features of planetary wave propagation on the sphere. Small zonal wave numbers propagate strongly polewards as well as eastwards, resulting in a wave train path similar to a great circle. Higher zonal wave numbers are trapped equatorward of the poleward flank of the westerly jet, resulting in a split between the two wave trains. This may lead to a possible blocking region downstream, where the smaller wave number, poleward wave train and the higher wave number, subtropical wave train are out of phase. The wave amplitude increases towards the pole due to the spherical domain and the basic state. Stationary wave solutions are possible only in regions of westerly wind. Some of these features become apparent only when the wave analysis is performed on the sphere rather than on a beta plane, particularly the great circle wave train path. Since all of these features are found in the observed and modelled wave train responses to anomalous forcing, it suggests that the propagation of forced, stationary, barotropic Rossby waves is one of the basic processes determining wave train teleconnection patterns in the atmosphere.

Discussion

The link between observational, modelling and theoretical studies of teleconnections and forced planetary waves in the atmosphere has been outlined briefly and a relationship with blocking episodes in the northern hemisphere has been described.

The success of the simple wave analysis in describing teleconnection patterns in the atmosphere is surprising since a large number of possibly important factors such as non-linearity, time variation and zonal asymmetry has been neglected. The role of these factors in teleconnections and blocking can be found only by further study. Simmons (1982) used the time mean flow in the troposphere, including zonal variations, rather than the zonal mean flow, as the basic state in a numerical model. He showed that this was important in determining the amplitude of the wave train response to subtropical forcing. Webster (1982) has studied the effect of the variation of the

basic zonal flow with the season of the year on the response to subtropical forcing in a numerical model.

All of the studies that have been described here have concentrated on the northern hemisphere, though the modelling and theoretical studies can be applied to the southern hemisphere. The lack of hemispheric coverage and long time series of upper tropospheric data in the southern hemisphere has prevented many observational studies of teleconnections in the southern hemisphere from being made. The recent completion of 10 years of archived southern hemisphere analysed grid-point data by the Australian Bureau of Meteorology may make such studies possible.

Acknowledgments

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