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Prominent Northern Hemisphere Winter Blocking Episodes and Associated Anomaly Fields of Sea Surface Temperatures

ERNEST C. KUNG[1], JOEL SUSSKIND[2] and CARLOS C. DACAMARA[3]

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ABSTRACT

From a 34-year data period, twelve major winter blocking episodes in the northern hemisphere are selected for examination: four episodes for each category of Pacific, Atlantic and double blocking. It is shown that the single blockings in the Pacific or Atlantic are formed through constructive interference of the traveling zonal wave of n=1 and stationary wave of n=2. The n=1 is supported by the energy input through the nonlinear wave-wave interaction, and the n=2 by in situ warming over the Pacific and Atlantic. The concurrent double blocking in the Pacific and Atlantic are formed by the stationary n=2 when the traveling n=1 is weak. The negative anomaly fields of sea surface temperatures in the Pacific and Atlantic are associated with the single blocking in the Pacific and Atlantic. On the contrary, the positive anomalies in both the Pacific and Atlantic are associated with concurrent Pacific and Atlantic blockings, indicating the baroclinic nature of the double blocking.

1. INTRODUCTION

The winter circulation in the northern hemisphere is often dominated by a sequence of blocking episodes in the Pacific and Atlantic regions in association with the activities of low-frequency planetary waves. It is noted that a considerable forecast skill exists for such persistent large-scale anomaly patterns (see Shukla, 1981; Holloway and West, 1984; Kung *et al.*, 1990), making the study of winter blocking particularly important. A major concern in this area of study has been the transition of the extratropical circulation from states dominated by transient synoptic-scale disturbances to the low-frequency regimes dominated by quasi-stationary planetary waves, and the maintenance of an established blocking pattern.

[1] Department of Soil and Atmospheric Sciences, University of Missouri-Columbia Columbia, Missouri, U.S.A.

[2] Laboratory for Atmospheres, Goddard Space Flight Center/NASA Greenbelt, Maryland, U.S.A.

[3] Department of Physics, Faculty of Science, University of Lisbon, Lisbon, Portugal.

Despite the known difficulty in precisely defining the blocking phenomena, the general characteristics of quasi-stationary ridges of blocking circulation are well recognized, and a wealth of literature exists on the subject since the early studies of Elliot and Smith (1949), Berggren *et al.* (1949), Rex (1950) and others. More recent development in this area was reviewed in Saltzman *et al.* (1986). During a blocking period, distinct obstruction of the northern hemisphere westerlies is apparent in and around the block. However, from the viewpoint of the major blocking, it is not a local system. As shown by many in recent years (e.g., Hansen and Chen, 1982; Hansen and Sutera, 1984; Kung and Baker, 1986; Kung *et al.*, 1990; Saltzman et al., 1986; Tanaka, *et al.* 1986; Vakalyuk, 1985), the diagnosis in the zonal spectral domain is an effective approach to reveal essential mechanisms involved in growth and maintenance of blocking patterns.

There have been diverging opinions on the energetics nature of blocking among researchers. Saltzman (1959), in his early study of the general circulation, proposed that the large-scale quasi-stationary systems are maintained by a nonlinear barotropic transfer of kinetic energy from smaller cyclonic-scale disturbances which have baroclinic energy sources. Diagnostic studies by Hansen and Chen (1982), Murakami and Tomatsu (1965), Paulin (1970) and others identified blocking phenomena with large-scale baroclinic conversion. However, Hansen and Sutera (1984), by contrasting the blocking and nonblocking periods, reported the significant wave-wave interactions to support the kinetic energy of blocking. From the vorticity consideration, Green (1977), Illari (1984), Shutts (1983) and others also demonstrated that the synoptic-scale eddy forcing supports the formation of blocking. Our preceding studies of observed and simulated blocking episodes (Kung and Baker, 1986; Kung *et al.*, 1989) revealed that the development of northern hemisphere winter blocking is associated with the nonlinear wave-wave transfer of kinetic energy from synoptic-scale disturbances to planetary waves. For observed blocking episodes during December 1978 and January 1979, Tanaka and Kung's (1988) energetics diagnosis in three-dimensional normal mode expansion depicted an ordinary transfer of energy from the zonal baroclinic component to the barotropic component of planetary waves via synoptic scale conversion. Kung *et al.* (1990) further demonstrated that a high resolution general circulation model is capable of producing two successive realistic blockings in the Pacific and Atlantic through one winter month in January 1979 if the sea surface temperature (SST) field is updated daily with observations during the model integration.

As blockings are a group of quasi-stationary circulation patterns of similar synoptic appearance, but likely of different causes and mechanisms involved, it is reasonable to find diverging diagnostic results among various case studies. To approach a problem of complexity such as blocking, both the case study and long-term climatological analysis are necessary. In our preceding work (DaCamara *et al.*, 1991) monthly circulation patterns of the northern hemisphere were analyzed with daily 500 mb field and monthly sea surface temperature (SST) anomaly field during 34 winter seasons from 1955 to 1989. All 102 monthly circulations were classified into 5 categories of patterns according to dominant blocking activities of the month: Pacific blocking, Atlantic blocking, double blocking, sequential blocking and no blocking. It appeared that, on the gross average, the Pacific, Atlantic and double blocking dominated winter circulation and can be associated with characteristic SST anomaly field in the Pacific and Atlantic. However, by taking the gross averages of the long-term period, variability among different cases can be easily masked. Thus a parallel case study of the same time period is highly desirable.

In this study, prominent major blocking episodes are the focus of our attention. Twelve major winter blocking episodes are selected from the daily analyses of 500 mb flow from 1956 to 1989: four episodes for each category of Pacific, Atlantic and double blocking. Through examination of prominent cases, this study attempts to distinguish the characteristics of these blockings in their development and maintenance. Manifestations of the blocking flow pattern are examined in terms of the geopotential height and associated anomaly fields. Activities of planetary waves are examined by trough-ridge diagrams, kinetic energy and its wave-wave interaction to provide energy input at zonal wavenumber n=1 and 2. The patterns of associated SST anomaly fields are then considered in terms of energy source for in situ baroclinic conversion and wave-wave interaction. It is noted that this is a case study and not an ensemble analysis, although twelve cases are more than the number of cases usually treated in most case studies. We are not attempting a composite climatological analysis of numerous blocking episodes during a long-term period. Such an attempt would be difficult, since various causes and thus various mechanisms may be involved in many cases of developing blocking. Rather, we would like to examine characteristics of major episodes in three categories of blocking development which show common prominent appearances in each category.

2. DATASETS AND SCHEME OF ANALYSIS

Datasets utilized in this study include the daily northern hemisphere geopotential height at 500 mb (Z) in December, January and February from December 1955 to February 1989, and monthly SST analyses for the same period. The Z fields are obtained from the daily National Meteorological Center (NMC) octagonal grid analyses at 1500 GMT from 1955 to 1957, and 1200 GMT for the rest of the period. The octagonal grid analyses are edited and bilinearly interpolated to a $4^\circ \times 5^\circ$ latitude-longitude spherical grid from 18°N to 90°N. The wind fields are computed using the geostrophic approximation, and their Fourier transforms are obtained at latitude circles 4° apart. Monthly SST analyses are acquired from the Comprehensive Ocean Atmosphere Data Set (Slutz *et al.*, 1985) for the period 1956-1979, and NMC real-time analyses (Reynolds, 1988) for the period 1970-1989. Consistency of both analyses is verified for the overlapping period, and a complete time series of 1956-1989 is generated at the $2^\circ \times 2^\circ$ grid. The Z and SST anomalies at each grid point are computed in reference to the 34-year mean value of the month.

A blocking is recognized when the blocking index I at longitude λ is greater than 50m along a longitudinal sector:

$$I(\lambda) = Z(\lambda, 62^\circ N) - Z(\lambda, 46^\circ N)$$

This index was originally introduced by Lejenäs and Økland (1983) and used in Kung *et al.* (1989,1990) with minor modifications. Positive values of I indicate the existence of a quasi-meridional dipole which is formed by a high-pressure cell poleward and a low-pressure area equatorward. The quasi-meridional dipole is a characteristic shared by both diffluent (Rextype, see Rex, 1950) and meridional (Ω-shaped) blockings. In the additional scan for cases of tilted orientation of meridional dipoles and cases of blocking partially out of the chosen latitudinal band, $Z(\lambda \pm 5^\circ, 62^\circ N)$ is substituted for $Z(\lambda, 62^\circ N)$ in computing the blocking index I. The blocking identified by I is verified by manual inspection of the flow pattern. Pacific and Atlantic are the two regions of preferred winter blocking activities in the northern hemisphere. The single dominant blockings in the Pacific and Atlantic are identified by PAC and ATL in this paper. The recurrence of blocking in the Pacific and Atlantic during the same general period constitute the double blocking, and are identified by DBL.

The kinetic energy at wavenumber n, K(n), and the nonlinear transfer of kinetic energy from wavenumber m to wavenumber n, L(n,m), are evaluated in reference to planetary wave activities. Evaluation of K(n) is described in Saltzman (1957) and our previous studies (e.g., Kung and Baker, 1986). The term L(n,m) for an open system, defined by two latitudinal walls and two isobaric surfaces, explicitly incorporates the fluxes across the boundary of the domain. Its evaluation is discussed by Kanamitsu (1980), Kanamitsu *et al.* (1972), and Tsay and Kao (1978). The evaluation in this study follows their formulation (see DaCamara *et al.*, 1991) and is detailed in Dacamara (1991). Since our analysis is based on the single level data at 500 mb, the vertical flux term is not involved in computation.

3. BLOCKING EPISODES AND PATTERNS OF CIRCULATION

Twelve major blocking episodes are selected from the daily analyses of 500 mb flow for the 34-year data period. They include four episodes, each in three categories: PAC, ATL and DBL. These episodes are identified in this paper as P1, P2, P3, P4 for PAC; A1, A2, A3, A4 for ATL; and D1, D2, D3, D4 for DBL. Table 1 lists periods, subperiods, primary locations, and short descriptions of development for each of twelve episodes. Of 108 winter months of the 34-year period, we document only 26 months without noticeable blocking activities (DaCamara *et al.*, 1991). All other months are under the dominance or influence of one of these three types of blocking. Episodes chosen in this study show prominent patterns of blocking circulation. However, they are chosen for their prominence and persistence to study their distinguished characteristics with least interference of secondary features.

As described in Table 1, each episode is a dominant and often recurring circulation pattern during the period. The lengths of periods identified for these episodes are from 25 days to 45 days. Figure 1 shows the time-longitude plots of the daily blocking index for all twelve episodes examined in this study. Initiation, development, decaying and re-enforcement of blocking are identified by manual examination of such time-longitude diagrams. Some subjective judgement is inevitable in identification, but as shown in Figure 1, identification is straightforward. A new blocking occurrence is generally recognized when the contour lines are not connected. It is shown in Figure 1 that the winter blockings in the Pacific and Atlantic are formed over the oceanic area, although they may extend into the continental area. From both Figure 1 and Table 1 it appears that the double blocking events are more intense and persistent than single blockings. However, the Pacific and Atlantic components of double blocking events are not exactly in phase with certain time lags between maxima in the Pacific and Atlantic. This may suggest involvement of traveling planetary waves. It is interesting to note that the persistent blocking episodes involve the recurrence of blocking patterns in the same general locations during the period of episodes. This may suggest the existence of prevailing boundary conditions that favor the development of blocking. The SST anomaly patterns will be examined in this regard later in this paper.

Figures 2, 3 and 4 are the 10-day mean circulation patterns and anomaly fields of Z between 20°N and the pole, for each episode of PAC, ATL and DBL when the blockings are fully developed. The prominence of the Pacific blocking in the northern hemisphere circulation is apparent in Figure 2. As the blocking dominates in the Pacific, the Atlantic is occupied by basically zonal flow. In the Pacific, the anomaly field is characterized by a sharp contrast of negative anomaly area in the south and positive area in the north. During the Atlantic blocking, the patterns in the Pacific and Atlantic are reversed (see Figure 3). During the double blocking the characteristic flow patterns and associated anomaly fields are seen in both the Pacific and Atlantic. However, examining Figures 2, 3 and 4, it is evident that the regions of blocking activities and contrast of positive and negative anomalies are more extensive in the Pacific than in the Atlantic. If the formation of winter blocking is to be related to SST anomaly pattern, this seems reasonable, since the oceanic area of the Pacific is much more extensive than that of the Atlantic.

Table 1. Selected major episodes of Pacific, Atlantic and double blocking.

Case	Period (day/mo/yr) and Number of days	Subperiod (day/mo)		Primary Location in 42-62°N	Description
P1	22/12/77	22-26/12		180-120°W	Developing Rex blocking
	-20/1/78	27/12-15/1		180-120°W	Fully developed Rex blocking
	(30days)	16-20/1		180-120°W	Decaying Omega blocking
P2	7/12/80	7-11/12		150°E-150°W	Identifiable Rex blocking
	-5/1/81	12-16/12		150°E-120°W	Decaying ridge
	(30days)	17-31/12	(1)	150°E-120°W	Fully developed Rex blocking
			(2)	120°E-180°	Slowly retrograding from (1) to (2)
		1-5/1		150°E-150°W	Inverted Omega blocking
P3	27/12/82	27-31/12		180-120°W	Developing Omega blocking
	-30/1/83	1-10/1		150°E-150°W	Fully developed Rex blocking
	(35days)	11-15/1		150°E-150°W	Decaying Omega blocking
		16-20/1		120-90°W	Developing Omega blocking
		21-25/1		180-120°W	Fully developed Omega blocking
		26-30/1		120-90°W	Decaying Omega blocking
P4	17/12/83	17-21/12		180-120°W	Omega blocking
	-20/1/84	22-26/12		180-120°W	Fully developed Rex blocking
	(35days)	27-31/12		180-120°W	Decaying ridge
		1-5/1		120-90°W	Developing ridge
		6-10/1		180-120°W	Developing Omega blocking
		11-15/1		180-120°W	Fully developed Omega blocking
		16-20/1		180-120°W	Decaying Omega blocking
A1	26/1-	26-30/1		30°W-30°E	Developing ridge
	24/2/66	31/1-4/2		60°W-0°	Developing Omega blocking
	(30 days)	5-14/2		60°W-0°	Fully developed Rex blocking
		15-19/2		60°W-0°	Omega blocking
		19-24/2		60°W-0°	Decaying ridge
A2	31/1-	31/1-4/2		60°W-0°	Developing Rex blocking
	24/2/69	5-14/2		60°W-0°	Fully developed Rex blocking
	(25 days)	15-19/2		90-30°W	Fully developed Omega blocking
		19-24/2		90-30°W	Decaying ridge
A3	27/12/71	27/12-10/1		30°W-30°E	Fully developed Rex blocking
	-20/1/72	11/1-15/1		30°W-60°E	Fully developed Rex blocking
	(25 days)	16-20/1		0-60°E	Fully developed Rex blocking
A4	11/1-	11-15/1		60°W-0°	Developing ridge
	14/2/79	16/1-4/2	(1)	60°W-0°	Fully developed Rex blocking
	(35 days)		(2)	90-30°W	Slowly retrograding from (1) to (2)
		5-14/2		60°W-0°	Fully developed Omega blocking

Table 1. (Continued.)

D1	6/1–4/2/57 (30 days)	6-10/1	(1) (2)	180–120°W 30°W–30°E	Omega blocking developing in both (1) and (2)
		11-20/1	(1) (2)	180–120°W 30°W–30°E	Fully developed Rex blocking in both (1) and (2)
		21-30/1	(1) (2)	180–120°W 0–60°E	Omega blocking in both (1) and (2)
		31/1–4/2	(1) (2)	180–120W 0–60°E	Decaying Omega blocking in both (1) and (2)
D2	7/12/61 –5/1/62 (30 days)	7-11/12	(1) (2)	180–120°W 30°W–30°E	Developing Omega blocking in both (1) and (2)
		12-21/12	(1) (2)	150°E–150°W 0–60°E	Fully developed Omega blocking in both (1) and (2)
		22-26/12	(1) (2)	120°E–180° 90–60°W	Fully developed Rex blocking in both (1) and (2)
		27-31/12	(1) (2)	120°E–180° 60°W–0°	Omega blocking in both (1) and (2)
		1-5/1	(1) (2)	150°E–150°W 60°W–0	Decaying ridges in both (1) and (2)
D3	22/12/62 –4/2/63 (45 days)	22-26/12	(1) (2)	180–120°W 30°W–30°E	Omega blocking in both (1) and (2)
		27/12-10/1	(1) (2)	150°E–150°W 60°W–0°	Fully developed Rex blocking in (1) and (2)
		11-25/1	(1) (2)	180°–120°W 30°W–30°E	Omega blocking in (1) and Rex blocking in (2)
		26-30/1	(1) (2)	180–120°W 60°W–0°	Fully developed Omega blocking in both (1) and (2)
		31/1–4/2	(1) (2)	150°E–150°W 60°W–0°	Rex blocking in (1) and Omega blocking in (2)
D4	26/1–29/2/68 (35 days)	26-30/1	(1) (2)	180°–120°W 30°W–30°E	Developing Omega blocking in (1) and developing ridge in (2)
		31/1–4/2	(1) (2)	120°E–180° 60°W–0°	Rex blocking in (1) and Omega blocking in (2)
		5-9/2	(1) (2)	120–90°W 60°W–0°	Omega blocking in both (1) and (2)
		10-19/2	(1) (2)	120–90°W 60°W–0°	Rex blocking in both (1) and (2)
		20-29/2	(1) (2)	120–90°W 30°W–30°E	Omega blocking in (1) and Rex blocking in (2)

Under the dominance of a single blocking in the Pacific or Atlantic, the amplification of the planetary wave n=1 is most obvious in the northern hemisphere circulation (Figures 2 and 3), whereas the amplification of n=2 occurs in the double blocking circulation (Figure 4). This situation may permit the treatment of major winter blockings in the zonal wavenumber domain despite their traditional, synoptic treatment as local manifestations. As the wave-wave interaction of kinetic energy is associated with the amplification of planetary waves, it is pertinent to conjecture that the constructive interference among planetary waves may be a factor for the development of a major winter blocking. Austin (1980) reported that n=1 and 2 tend to interfere constructively in the Atlantic sector, and n=2 and 3 interfere in the Pacific sector. In our preceding study (Kung *et al.*, 1990), it was suggested that during the development of a Pacific blocking in January 1979, n=1 and 2 came in place at the location

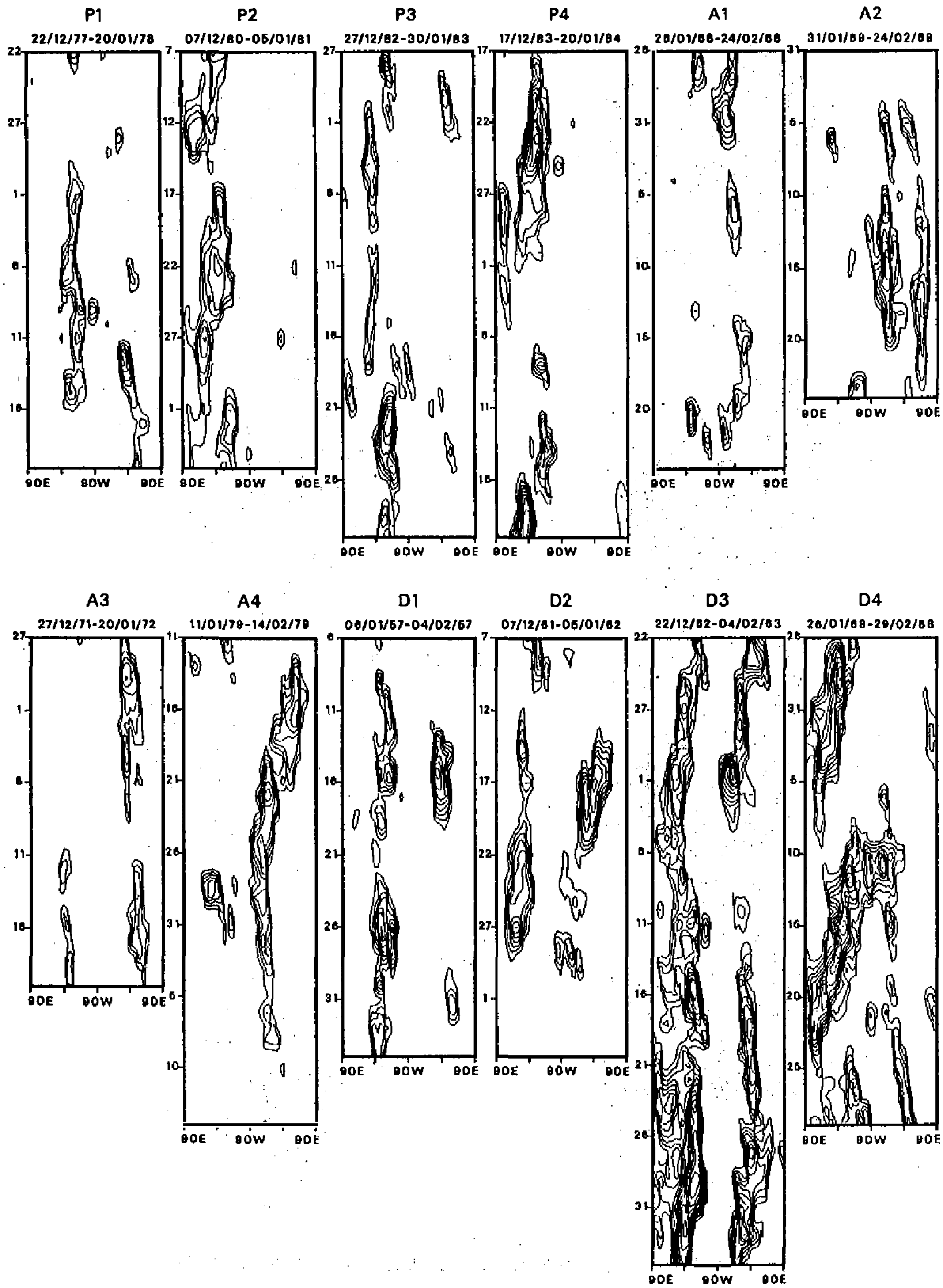

Fig. 1. Time-longitude plots of blocking index for 0 and positive values with contour interval of 50 m.

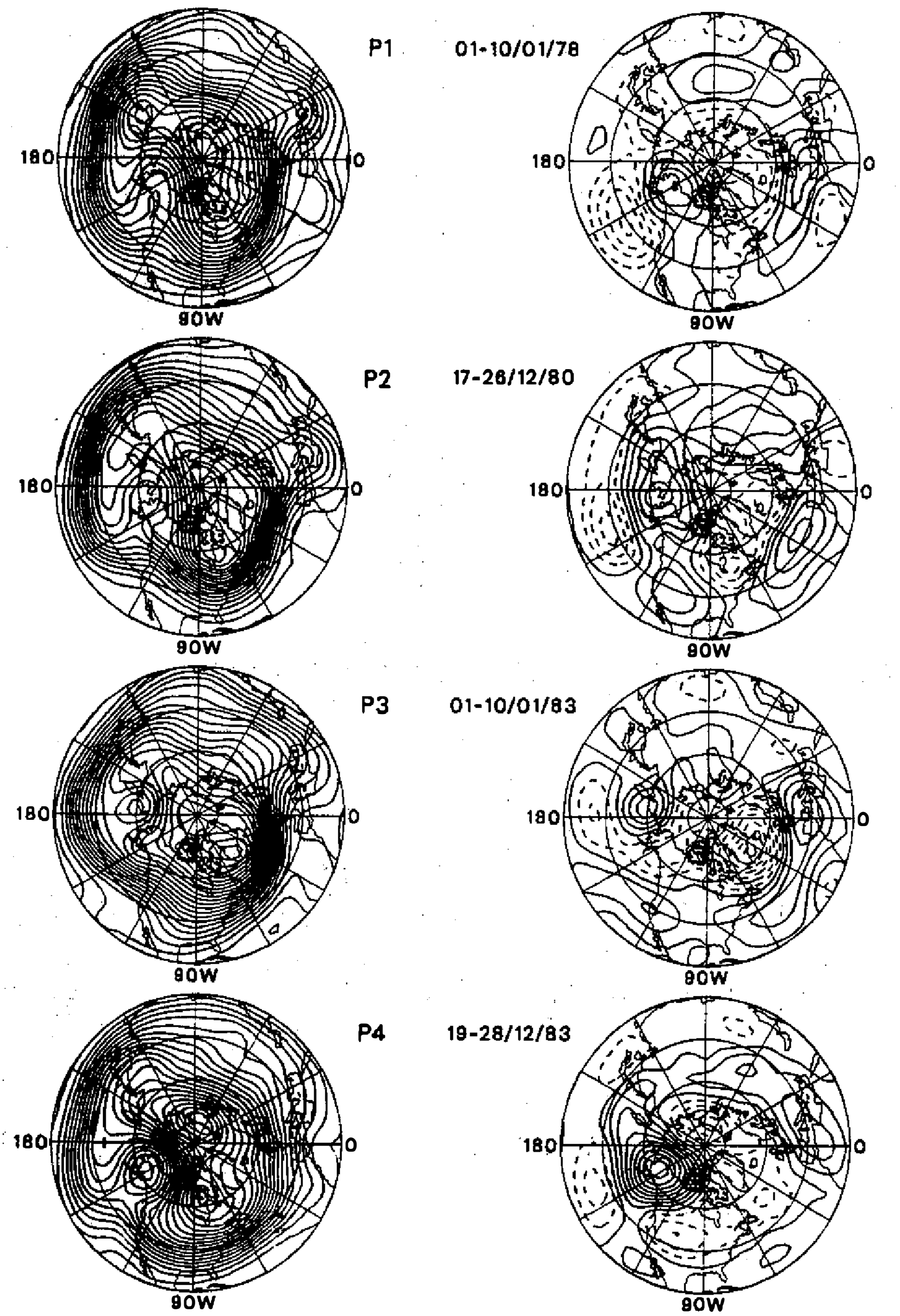

Fig. 2. Patterns of 10-day mean 500 mb circulation and anomaly fields of Z from 20° to 90°N during the fully developed episodes of PAC. The contour interval is 50 m and negative contour lines are dashed.

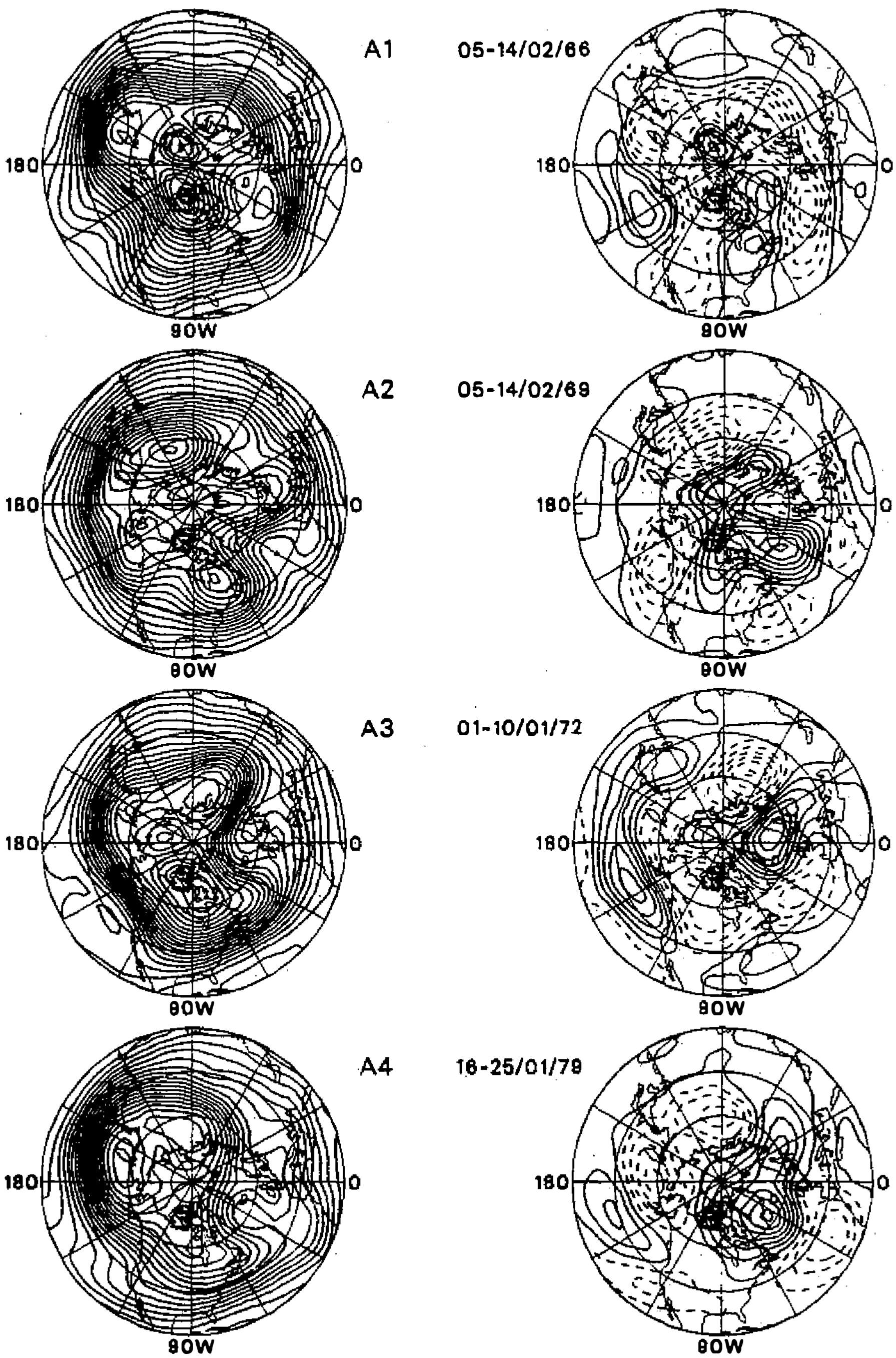

Fig. 3. As in Figure 2, but for ATL.

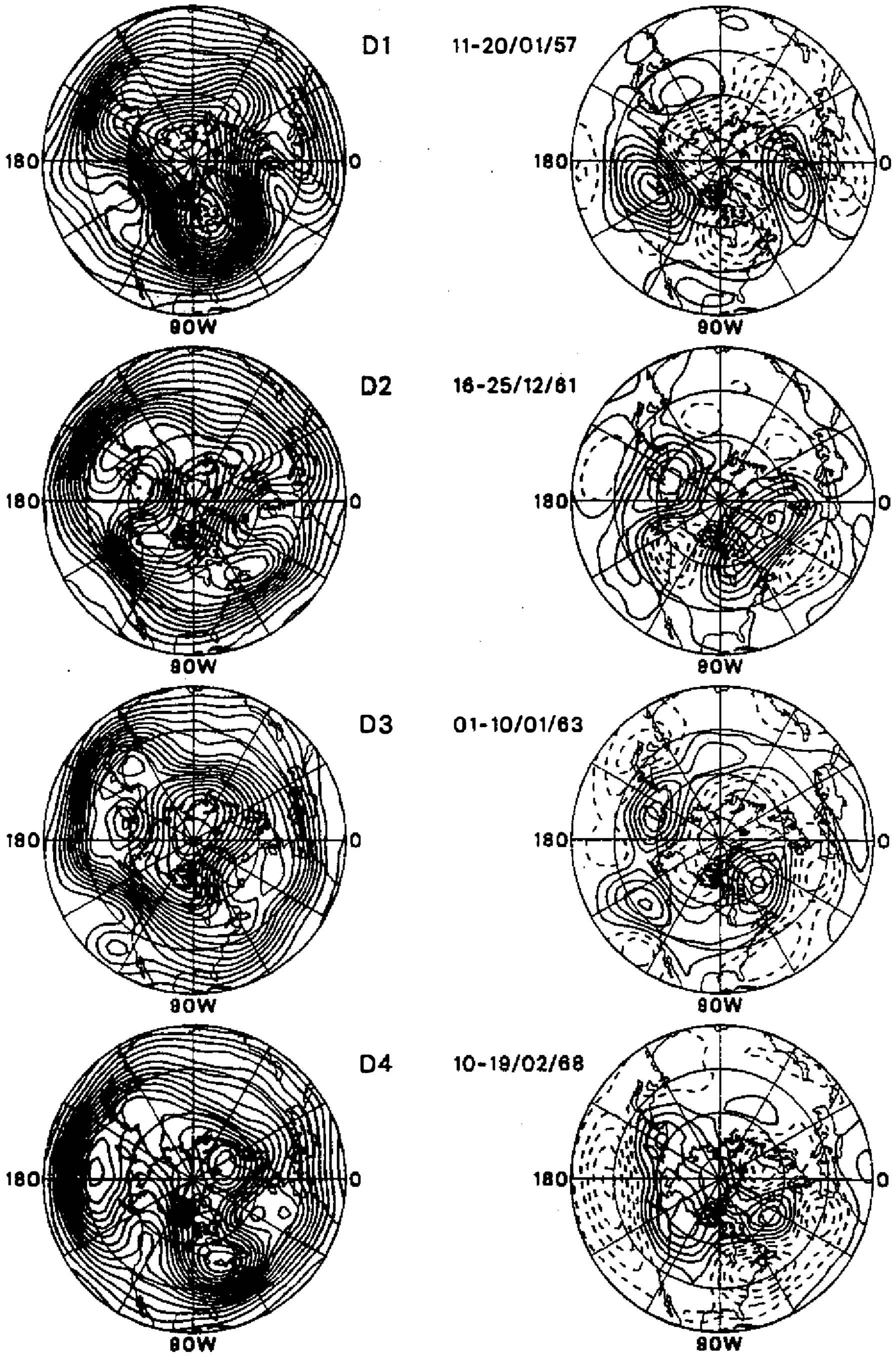

Fig. 4. As in Figure 3, but for DBL.

of the block. Toward the end of the same month the interference of n=1 and 2 in the Atlantic was identified with the development of a major Atlantic blocking.

The interference of n=1 and 2 is confirmed with all episodes selected in this study. Figure 5 demonstrates for one episode in each of three blocking categories the 500 mb trough-ridge diagrams for n=1 and 2 in the 54°-70° band. Although the blocking index is defined between 46° and 62°N to account for the general pattern of circulation, the 54°-70°N

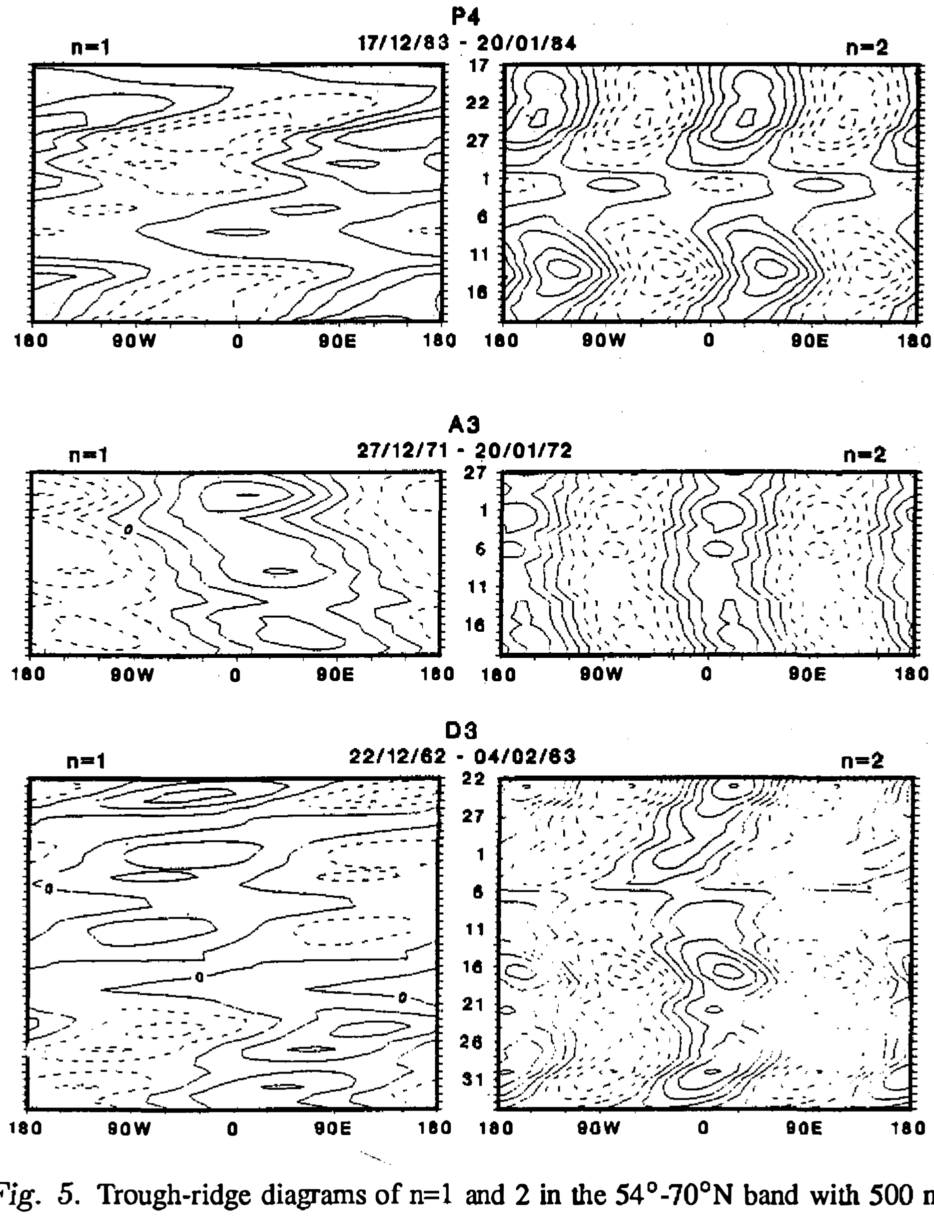

Fig. 5. Trough-ridge diagrams of n=1 and 2 in the 54°-70°N band with 500 mb Z during blocking episodes of P4 (PAC), A3 (ATL) and D3 (DBL). The contour interval is 50 m, and negative contour lines are dashed.

band is used in this application because it is the latitudinal band in which the blocking pattern is maximized. It is noteworthy that the primary locations of major blocking episodes (as indicated in Table 1) during the course of blocking development are the longitudinal segments where n=1 and 2 interfere constructively. Madden (1983) found that the interferences of stationary and traveling waves of the same longitudinal scale cause time variations in the large-scale circulation. It is noted in Figure 5 that the positions of n=2 maximum amplitude stay approximately the same in the general area of 0^{o} and 180^{o} throughout the winter, although the strength of the wave is apparently subject to time variation. On the contrary, the phase angle of n=1, in addition to the amplitude, is variable, indicating that n=1 travels slowly around the northern hemisphere. It is seen here that, when the traveling n=1 constructively interferes with the stationary n=2, the major blocking develops. If n=1 is relatively weak and n=2 is strong, n=2 is responsible for creating the double blocking pattern, as is the case of D3 shown in Figure 5. It is also noteworthy that weakening and redeveloping blocking in the same blocking episodes, as identified in Table 1, correspond with the periodic weakening and amplifying of n=1 and 2.

A comprehensive energetics description is not the purpose of this paper. Neither is it possible with the dataset of this study to compute energy transformations, except for nonlinear interactions at the 500 mb level. Thus only the kinetic energy K and nonlinear transfer L are presented in Figures 6 and 7 to describe characteristic meridional distribution of K(n) for n=1,2 and 3 for PAC, ATL, and DBL episodes and associated L(n,m) in reference to n=1. The characteristics of circulation are first observed by K(n) as kinetic energy and represent the strength of circulation. Examination of L(n) is pertinent for blocking cases, since the development and maintenance of blocking are closely associated with the nonlinear transfer of kinetic energy, which provides the barotropic energy source (Kung and Baker, 1986; Kung *et al.*, 1989). As shown in Figure 6, K(1) of PAC is most pronounced among the three categories of blocking, and is also least unstable from episode to episode. For ATL, K(1) is less pronounced than for PAC, which is consistent with the observation that the Pacific blocking is more dominant than the Atlantic blocking (see Figures 2 and 3). For DBL episodes, K(2) is most pronounced among planetary waves, as expected from the dominance of the n=2 pattern.

The L(1), the input of kinetic energy to n=1 from all other waves, and L(1,2), the input of kinetic energy from n=2 to n=1, are most pronounced for PAC, as seen in Figure 7. This indicates that the traveling n=1 (see Figure 5) has its source at n=2 in forming the Pacific blocking. In the case of DBL, n=1 is also maintained by n=2 through L(1,2), but the magnitude of K(1) is much less than for PAC. For ATL the barotropic energy source of n=1 is not at n=2. An earlier case study of an ATL episode by Kung and Baker (1986) shows that during the development stage of an atlantic blocking n=1 is supported by nonlinear interaction with synoptic scales smaller than n=3. It is also noted in this study, though not shown in Figure 7, for all three categories of blocking situation the wave-wave energy input into n=2 is very small: negative for PAC and ATL and only slightly positive for DBL. Thus the energy source at n=2 should come from the baroclinic conversion, both for the maintenance of n=2 itself and in support of transformation to n=1.

4. SEA SURFACE TEMPERATURE ANOMALIES AND BLOCKING

From the foregoing discussion of planetary wave activities, it may be questioned if the three categories of major winter blocking are associated with different types of energetics forcing. It is generally recognized that the SST anomaly fields exercise a major control over

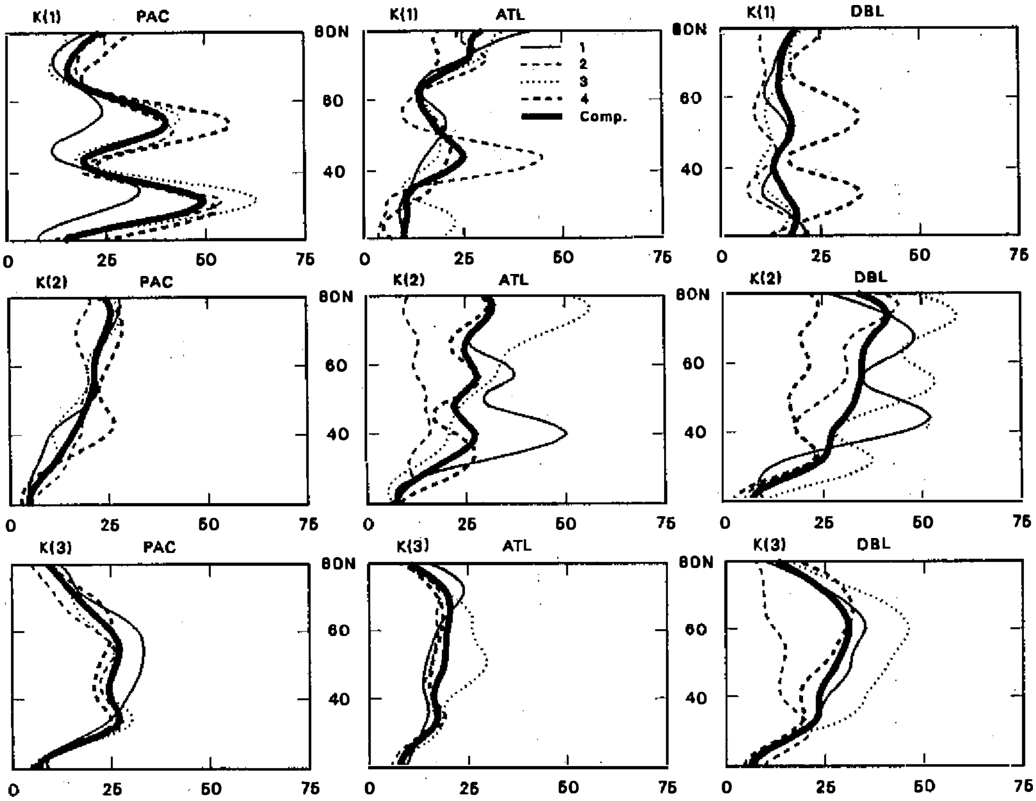

Fig. 6. Meridional distributions of kinetic energy K(n) for n=1, 2 and 3 in units of m^2s^{-2} for four episodes and their mean for PAC, ATL and DBL.

the winter circulation through heat release in the ocean-atmosphere interaction (e.g., Kung *et al.*, 1990; Namias, 1959, 1978; Wallace *et al.*, 1990). The patterns of SST anomalies are examined in reference to the major blocking episodes in this study.

Anomalies of Z and SST are averaged for four episodes in each blocking category, and shown in Figure 8 for the area between 20° and 60°N. Blocking area includes both the positive area of Z anomalies in higher latitudes and negative area in lower latitudes. Because the northern boundary of the area in the figure is 60°N, the positive anomalies of Z in the higher latitudes are only partially shown for blocking episodes (see Figures 2,3, and 4). Yet the sharp contrast of positive Z anomalies in the north and negative anomalies in the south are well recognized in the Pacific for PAC, in the Atlantic for ATL, and in both Pacific and Atlantic for DBL. It is noted that the areas of blocking both in the Pacific and Atlantic tend to appear in lower latitudes for DBL than for PAC and ATL.

In Figure 8, it is evident that PAC episodes are associated with the generally negative SST anomalies in the middle-latitude Pacific and western Atlantic. For ATL episodes the negative anomalies of SST are found in the middle-latitude Atlantic and eastern Pacific. However, the negative anomalies found in the average pattern of ATL in Figure 8 are not as distinctive as the negative anomalies for PAC. Yet, as shown in Figure 9, SST anomalies of individual ATL episodes are as distinct as those of PAC episodes. As the location of the

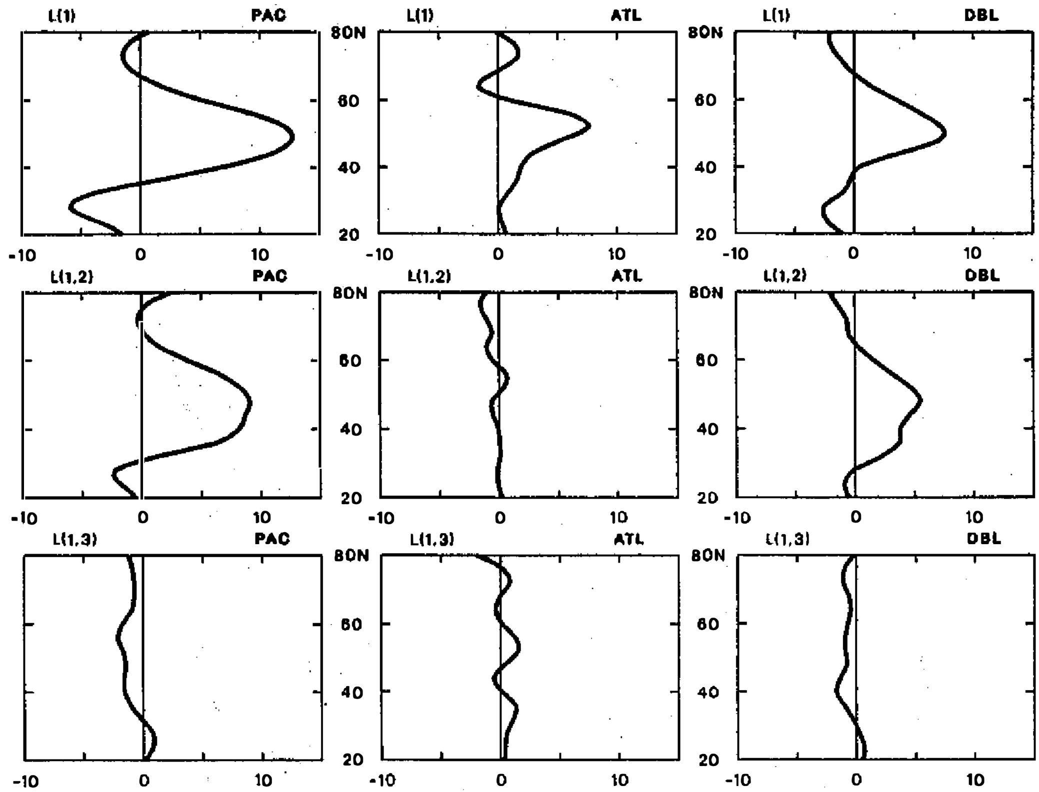

Fig. 7. Meridional distributions of kinetic energy input at n=1 by nonlinear wave-wave interaction L(1), and its component from n=2 and 3, L(1,2) and L(1,3), in units of $10^{-5} m^2 s^{-3}$ for composites of PAC, ATL and DBL.

negative Atlantic SST anomalies is more variable than for PAC episodes, the average pattern becomes less distinct. This seems to be related with the fact that the circulation pattern of ATL episodes is more variable than that of PAC episodes, as evident in the circulation patterns of Figures 2 and 3 and latitudinal distributions of K(1) and K(2) in Figure 6. Comparing the PAC and ATL episodes, it is apparent that general negative SST anomalies in the Pacific and Atlantic favor the development of major single blocking in the Pacific. When the negative pattern is limited to the Atlantic and part of the Pacific, with positive anomalies in the Pacific, a single blocking is likely to develop in the Atlantic.

The SST anomalies of DBL in Figures 8 and 9 show definitive positive patterns in most areas of the Pacific and Atlantic. This is a sharp contrast with SST anomaly patterns in PAC and ATL situations where the negative SST anomalies are associated with dominant single blocking. It is noted in the preceding section that the double blocking situation is developed and maintained by the stationary n=2 (Figure 5). The dominant n=2 should be supported by the baroclinic energy source since no barotropic energy is available for n=2 through nonlinear wave-wave interaction. The positive SST anomalies associated with DBL indeed indicate that the double blockings are developed with in situ warming of the northern hemisphere

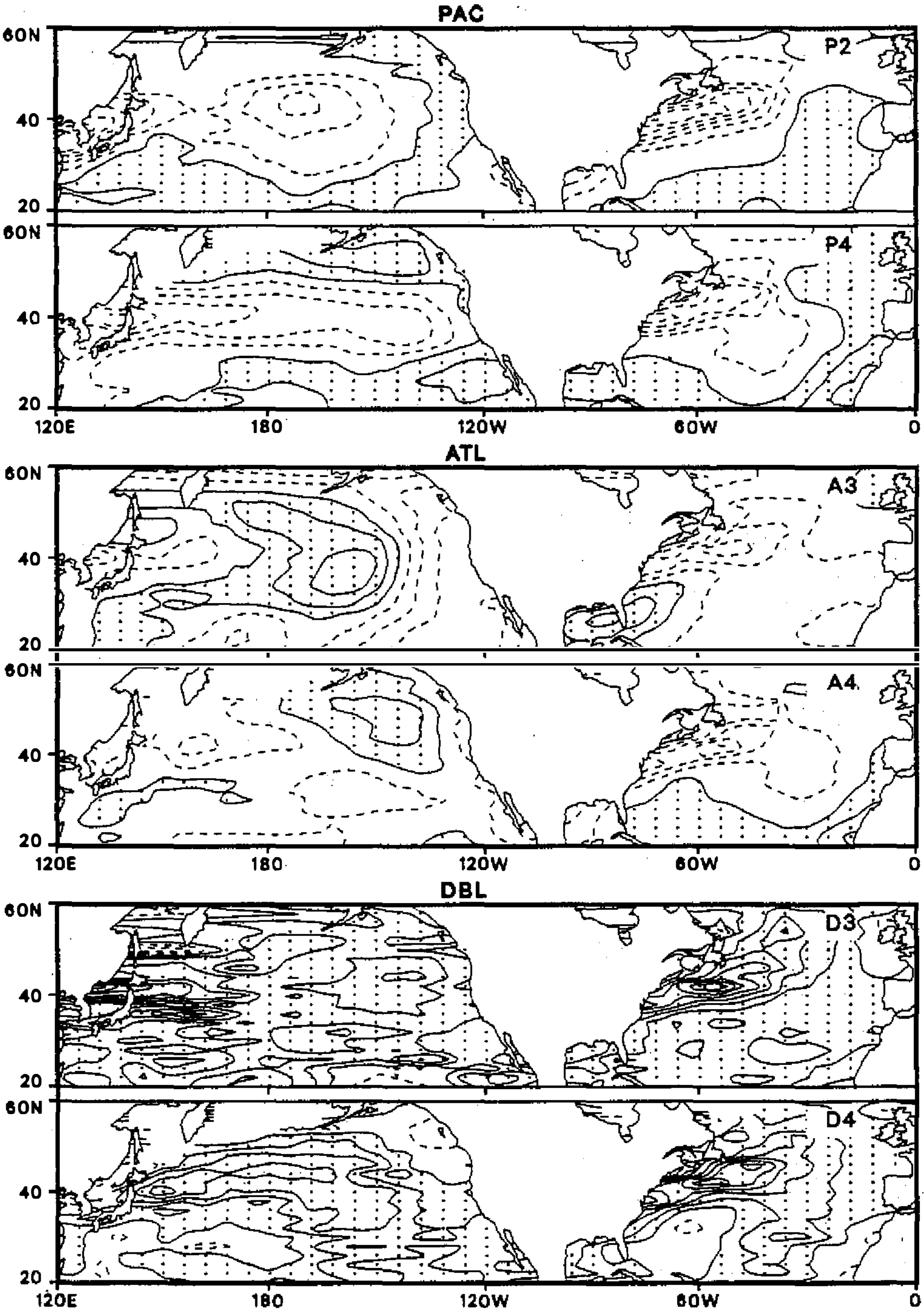

Fig. 8. Anomaly patterns of 500 mb Z and SST for composites of episodes for PAC, ATL and DBL. The contour interval is 50 m for Z and 0.5°C for SST. Negative contour lines are dashed.

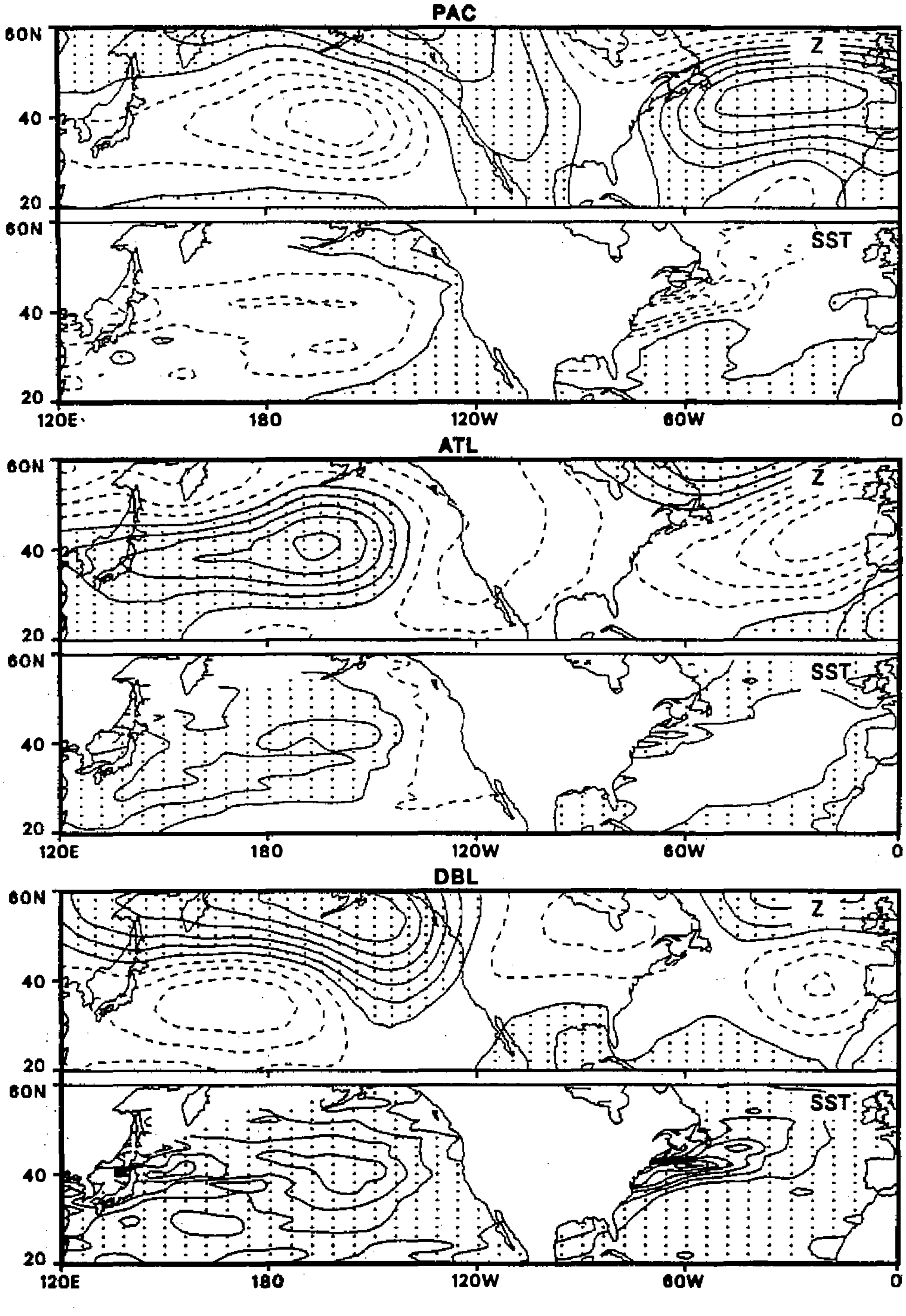

Fig. 9. Anomaly patterns of SST associated with blocking episodes of PAC (P2 and P4), ATL (A3 and A4) and DBL (D3 and D4). The contour interval is 0.5°C, and negative contour lines are dashed.

circulation. The negative SST anomalies associated with PAC and ATL then can be interpreted to favor the nonlinear wave-wave interaction to maintain the traveling n=1 that couples existing n=2 to form a single blocking pattern. The distinct energetics difference of single and double blocking patterns shown by these cases are interesting. The prominent double blocking pattern is baroclinic in nature whereas the occurrence of single major blocking depends on the barotropic nonlinear process of energy input.

5. CONCLUDING REMARKS

Because of the long characteristic time of SST variation and consequent persistence of blocking pattern, the study of blocking in relation with SST anomalies may have relevance in the long-range forecasting of the northern hemisphere winter circulation. With twelve prominent blocking episodes during the 34-year data period, this study has shown that the major single blockings in the northern hemisphere winter circulation are developed in the Pacific or Atlantic trough constructive interference of traveling n=1 and stationary n=2. The former is supported by the nonlinear wave-wave interaction of kinetic energy, and the latter by the in situ warming over the Pacific and Atlantic. The double blockings situation in the Pacific and Atlantic is formed by n=2 when the traveling n=1 is weak. These planetary wave activities are seemingly associated with the accompanying SST anomaly patterns during these major blocking episodes. The negative SST anomalies of the Pacific and Atlantic are associated with PAC and ATL, whereas the in situ warming in both the Pacific and Atlantic is associated with DBL.

For the purpose of focusing on prominent major blocking situations, the approach taken in this study is that of case examination with only twelve major blocking episodes. As such, the results discussed only apply to major blocking episodes studied in this paper, and cannot be generalized to other blocking circulations. However, the results of this case study may offer useful information in considering the formation and maintenance of the northern hemisphere winter blockings. At present, a composite diagnosis of all winter blocking episodes during the 1956-1991 period is in progress in terms of planetary wave activities and will be reported subsequently.

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