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Northern hemisphere circulation regimes during the extremes of the El Niño/Southern Oscillation

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ABSTRACT

Mid-latitude circulation regimes affected by the El Niño/Southern Oscillation (ENSO) warm and cold extremes are analysed using a daily data catalogue (after Dzerdzeevskii) of 36 different hemispheric circulation patterns per season. These patterns are combined to form a bimodal structure of predominantly zonal and meridional steering of the cyclones and anticyclones. The largest ENSO response of these modes is observed in winter seasons at the end of the year of the event with enhanced zonality (meridionality) responding to warm (cold) episodes. Individual circulation patterns show that a warm event forces the storm track across the North Pacific into a more zonal direction, in particular its more sensitive tail in the eastern region. Furthermore, the distribution of residence times of the circulation regimes reveals an enhanced warm event response of short period (4–8 days) disturbances associated with a larger zonal wavenumber.

1. Introduction

One reason to investigate warm and cold El Niño/Southern Oscillation (ENSO) extremes is their possible influence on the seasonal weather anomalies far distant from the forcing region. Given that a global effect of ENSO exists, long-range forecasts for areas remote from the tropical Pacific may be possible from predictions of the evolution of ENSO. In particular, the ENSO signature on the mid-latitude wintertime atmosphere has been analysed by numerous general circulation model (GCM) experiments (see, for example, Mechoso et al., 1987; Geisler et al., 1985; Palmer and Mansfield, 1986a and b) and diagnostic data analyses (see for example, Namias and Cayan, 1984; Hamilton, 1988; van Loon and Madden, 1981; van Loon and Rogers, 1981; Horel and Wallace, 1981; Hansen et al., 1989). However, there is also evidence that extratropical wintertime circulation anomalies are "more sensitive to certain extratropical sea surface temperature anomalies than to anomalies associated with El Niño" (Wallace and Jiang, 1987) and that considerable variability characterizes the observed mid-latitude responses on various ENSO extremes.

Most diagnostic data analyses of the ENSO signature are based on standard atmospheric circulation statistics in terms of means, covariances (with and without time-lag) and fluxes, space-time filtered or cross-spectral properties of the basic meteorological field variables: e.g., mean temperature anomalies, eddy transports, energy conversion and their space-time variance densities, etc. In this sense *physical* bulk properties of the ENSO response are analysed. But, to gain a complete picture of the whole process, the physical data analysis needs to be complemented. One contribution comes from a more *mathematical* approach towards analysing ENSO model or observational data. This leads to the question of a possible existence of an attractor. From its static and dynamic properties (i.e., dimension and entropy) the degrees of freedom involved and the predictability of the process can be deduced (Fraedrich, 1988). The other contribution, which is the theme of this paper, lies in a more *phenomenological* approach towards the atmospheric circulation influenced by ENSO. This approach is more closely related to real weather phenomena represented by structurally stable or generic processes: common examples are tropical and mid-latitude cyclones and their space-time statistics leading to storm tracks and their variability.

In this study, we adopt the approach of traditional phenomenological circulation statistics to describe the impact of the El Niño/Southern Oscillation (ENSO) warm and cold events on the extratropical atmosphere: large-scale weather patterns (or Grosswetterlage, after Baur, 1951) are analysed to characterize the synoptic situation of the Northern Hemisphere (NH) qualitatively in terms of the track of cyclones and anticyclones in the mid-latitudes. Thereby, use is made of the uncommon data set of the Dzerdzeevskii (1962, 1975) classification of the mid- and higher-latitude synoptic scale circulation mechanisms (hemispheric circulation patterns). This data set is unique in the sense that it describes atmospheric states in qualitative or phenomenological terms (north of about 30° N) by the zonality or meridionality of cyclone and anticyclone trajectories providing quantitative time statistics. The climatology of this binary state time series of the two basic modes of zonal and meridional circulation and its response on ENSO extremes is analysed in Section 3.

2. Data and methods of analysis

2.1. *Northern hemispheric circulation states (after Dzerdzeevskii)*

A catalogue of 86 years of daily circulation patterns (December 1899 to November 1985) describes elementary atmospheric regimes of the whole Northern Hemisphere (polewards of about 30° N). Every day is given one (of 42) class or type of circulation patterns based on surface pressure data and, since 1953, on available aerological information and satellite imagary (Dzerdzeevskii, 1962, 1975, and issued on a regular basis). Not unlike the regional European Grosswetter (after Hess and Brezowsky, 1977), which characterizes the centers of action, their position and steering in the North-Eastern Atlantic/European sector, the Dzerdzeevskii circulation patterns are based on the synoptic scale processes, i.e., on the zonality and meridionality of cyclone and anticyclone trajectories in the Northern Hemisphere mid- and high latitudes. These patterns tend to dominate the circulation over a time span of a few days. Dzerdzeevskii (1962) defined 13 groups, examples from four of which are shown in Fig. 1. These groups can be reduced to a set of two complementary circulation regimes of predominantly zonal ($Z=1$) and meridional ($M=0$) trajectories of Northern Hemisphere synoptic scale systems. This leads to a binary stochastic circulation process which consists of a time series, $G(t)$, sampled on a day-to-day basis:

$$G(t)=Z \qquad \text{or} \qquad M$$

characterizing two regimes or states of the mid- and higher latitude flow. The *zonal* state contains circulation types which are either purely zonal with a ring of cyclone tracks around an Arctic anticyclone or disturbed by only one Arctic intrusion or block in higher latitudes; further differentiation is made by a lower latitude wavenumber in the subtropical belt given by the number and position of high pressure cells. The *meridional* state is described by the remaining types, depending on the zonal wavenumber in higher and lower latitudes, i.e., the number of polar vortices and interruptions of the subtropical high pressure belt (which is relatively large compared to the zonal state). In addition, some circulation types exist only in summer, others only in winter seasons, so that the 42 classes (including an undefined one) reduce to 36 circulation types per season which are combined to 13 groups. This zonal-meridional set of binary states has been used to describe the long-term trends and fluctuations in the Northern Hemisphere circulation (Dzerdzeevskii, 1971; Olberg, 1977) and will also be used here.

2.2. *El Niño/Southern Oscillation (ENSO) warm and cold events*

The ENSO episodes cover an idealized 2-year period centered at the year of the event with two seasons preceding and following it. The warm episodes are taken from Rasmusson and Carpenter (1983, their table 2 plus the warm event 1982) and the cold events are given by van Loon and Shea (1985, their table 1 plus the year 1975). The 19 warm event years occur at 1902, 1905, 1911, 1914,

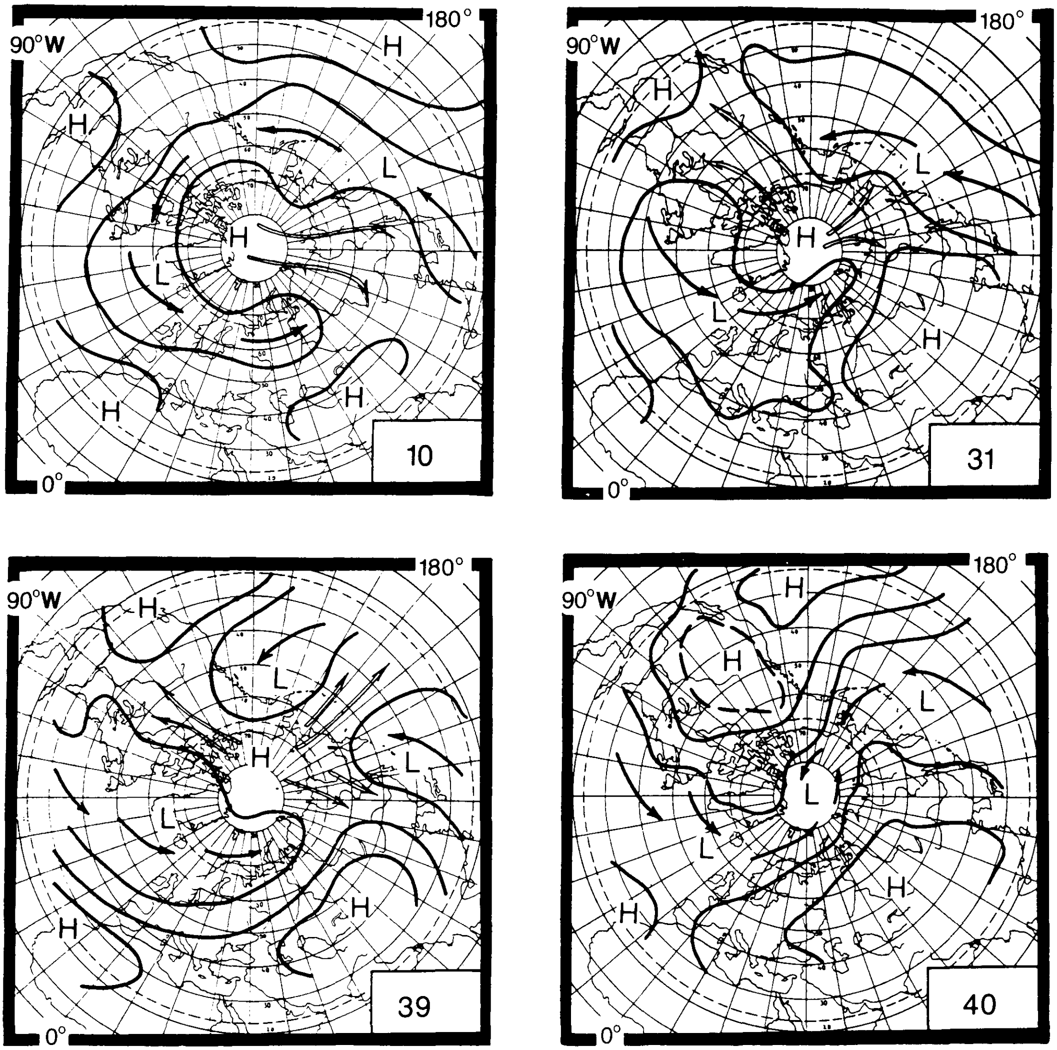

Fig. 1. A sample of four Northern Hemispheric circulation states (from Dzerdzeevskii, 1975), which contribute most to the number of days changing in response to the warm (top, 10 and 31) and cold (bottom, 39 and 40) El Niño/Southern Oscillation (ENSO) extremes. They are characterized by zonality (top pair) and meridionality (bottom pair) in the North Pacific region. Solid arrows: common tracks of travelling depressions; double arrows: common paths of high pressure centres or advancing ridges. Note that the extratropical responses to the 1982 and 1976 ENSO warm events show differences similar to the pair 10 and 31 (top) with relatively mild conditions over North America in the winter of 1982/83, and the severe conditions in 1976/77 (see, e.g., Palmer and Mansfield, 1986b).

1918, 1923, 1925, 1930, 1932, 1939, 1941, 1951, 1953, 1957, 1965, 1969, 1972, 1976, 1982. The 17 cold event years are 1903, 1906, 1908, 1916, 1920, 1924, 1931, 1938, 1942, 1949, 1954, 1964, 1966, 1970, 1973, 1975, 1978. The binary circulation states are composited around these warm and cold events.

3. ENSO response of the northern hemispheric circulation states (after Dzerdzeevskii)

The seasonal number of days occupied by the zonal circulation state is analysed

$$N(i, j) = \sum G(t) \qquad \text{for} \qquad t = T(i, j),$$

where $T(i, j)$ are the sequence of all 90 days of the four seasons ($i = 1, ..., 4$) running through the years ($j = 1889$ to 1985); for example, $i = 1$ is the December of the past plus the January and February of the current year, j. The number, $N(i, j)$, of days occupied by the zonal state is ranked, $r(i, j) = 1, ..., 86$ for each season i from the smallest to the largest values of the 86 years:

$$N(i, 1) < \cdots < N(i, r) < \cdots < N(i, 86).$$

The percentile ranks, $R(i, j) = 100r/86$, are then composed (see e.g. Ropelewski and Halpert, 1986; Fraedrich, 1990) with respect to the El Niño/Southern Oscillation warm and cold events before analysing the circulation statistics in the season of the strongest response. The composites around the warm and cold events run from the summer ($i = 3$) of the preceding year ($j - 1$) through spring ($i = 2$) of the following ($j + 1$) year:

$$\langle R(i, j) \rangle \quad \text{from} \quad (i = 3; j - 1)$$
$$\text{to} \quad (i = 2; j + 1)$$
$$\text{for} \quad j = \text{warm or cold years.}$$

The ensemble averages, $\langle\ \rangle$, are shown in Fig. 2, centered at the 50% level to visualize the deviations from the long-term mean, $\langle R(i, j) \rangle = 0.5 + 0.5/J$, with a total of $J = 86$ years; the variance is $(1 - 1/J^2)/12$, which tends to a standard deviation of $+/-28.9\%$. As the zonal and meridional hemispheric circulation modes are mutually exclusive, the zonal percentage ranks $\langle R(i, j) \rangle$ correspond to $1 - \langle R(i, j) \rangle$ for the meridional rank.

3.1. The response on ENSO extremes

The seasonal numbers of zonal circulation states are composed in terms of percentile ranks, $\langle R(i, j) \rangle$, about the warm and cold ENSO extremes (Fig. 2).

(i) The largest response occurs in the winter season (December through February) at the end of the warm event with strongly enhanced zonality (or reduced meridionality) of the hemispheric circulation; in the following spring, the regime reverses to reduced zonality (enhanced meridionality). The cold event response shows opposing signals of lesser intensity in these two seasons, whereas in the preceding seasons, similar (but less intense) responses of enhanced zonality are observed for both warm and cold events. Finally, there is a signal preceding the year of the event which shows reduced (enhanced) zonality for cold (warm) ENSO episodes. A physical interpretation of this effect is difficult. Furthermore, relatively smooth

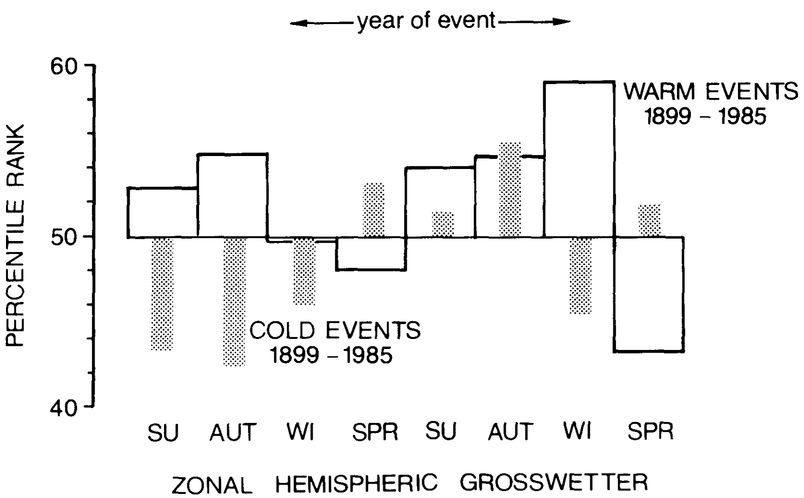

Fig. 2. Percentile ranks of the number of days of the zonal circulation state composed around El Niño/Southern Oscillation warm and cold events. The seasonal percentile rank values represent an average over 19 warm (open columns) and 17 cold events (stippled columns). The composite includes two seasons preceding and following the year of the event. (The seasons from spring to winter are denoted by SPR, SU, AUT, WI.)

transitions from reduced to enhanced hemispheric zonality are realized during the whole two-year cold episode composite, revealing a quasi-biannual wave. However, one observes two maxima of enhanced zonality (reduced meridionality) during the two-year warm event composite.

(ii) The distribution-free Wilcoxon (or Mann-Whitney) one-sided rank sum test provides the following test statistic of the percentile ranks: For $\langle R(i,j)\rangle > 0.5$ it is $R(90\%) = \{[m(N-m) + m'(m'+1)]/2 + 1.28[m(N-m)(N+1)/12]^{1/2}\}/Nm$; $m = m' = 19$ (17) is the number of warm (cold) events and $N = 86$. For $\langle R(i,j)\rangle < 0.5$, $m' = N - m$ and the test statistic is $R'(90\%) = (N+1)/2m - R(90\%)$. The related significance levels for warm events are $\langle R(i,j)\rangle < 0.43$ (> 0.57); for cold events $\langle R(i,j)\rangle < 0.42$ (> 0.58). The warm event winter and spring responses at the end of the year of the event pass this significance test (but hardly the autumn signal before the year of the cold event), i.e., the null-hypothesis can be rejected with 90% significance that the warm or cold circulation states belong to the same statistical population as their respective complements. In this sense, we may accept the winter and spring response of the zonal state on warm ENSO events as 90% significant after the effect signal, because it is also confirmed by ENSO response studies based on GCM experiments and data analyses (see, Horel and Wallace, 1981). Thus the following discussion of ENSO affected mid-latitude circulation states is confined to the winter season at the end of the event and the interpretations should be assessed under the caveat that they describe response mechanisms after the effect.

Individual circulation patterns (shown in Fig. 1) can be associated with the difference between the warm and cold events of zonal circulation states (which is largest in winter). They characterize a notable regional difference over the North Pacific where they reveal a marked zonality during warm event winters (top: circulation types 10 and 31) but meridionality during cold episode winters (bottom: circulation types 39 and 40). Only the circulation type 10 belongs to the binary set of hemispheric zonality ($Z = 1$), whereas 31, 39 and 40 are meridional states. The frequency distributions (not shown) of the particular circulation pairs 10, 31 and 39, 40 (Fig. 1) change considerably from warm to cold event winters. The null-hypothesis of cold and warm winters belonging to the same population is rejected on a 95% significance level using the Kolmogoroff–Smirnov test. This is also reflected by the average numbers of circulation states per warm/cold season whose difference (discussed in the following) is significant on the 95% level (based on the one-sided Student t-test). Almost a quarter of the average (86 years) winter days are occupied by these 4 out of 36 possible types, i.e., about 11 or 10 days for the North Pacific zonal or meridional pairs (top and bottom of Fig. 1). However, in the average winter season composed of the 19 warm events, the zonal circulation state in the North Pacific increases by about 50% to 14.7 days, whereas it reduces to 7.6 days in winters following the 17 cold episodes. North Pacific meridionality (types 39 and 40) changes inversely: residence times are about half of the average (4.1 days) in winter seasons at the end of warm event years, but they increase to 13.7 days for cold episodes. Here, it should be noted that Held et al. (1989, Fig. 8) document an equatorwards shift of the eastern half of the cross Pacific storm track in ENSO warm episodes and a more meridional (that is south west-north east) direction during cold events.

The two circulation types (10 and 31; Fig. 1, top) which are prominent during the warm event response both show North Pacific zonality but describe two opposing modes over North America. In a qualitative sense, they correspond with the observed extra-tropical response patterns on El Niño forcing; the 1982/83 ENSO warm event winter was relatively mild over North America (type 10), whereas 1976/77 induced severe conditions (type 31). Furthermore, they closely resemble the respective anomaly fields shown by Palmer and Mansfield (1986b. Fig. 9 and 17).

3.2. Distributions of circulation regimes

The duration, $L(Z)$ or $L(M)$, of a spell of hemispheric zonality or meridionality is the residence time which the atmosphere spends in succession in that mode or state. The associated distribution of the zonal circulation state is formally defined by

$$P(L(Z)=n) = \text{prob}\{G(t+(n+1)) = G(t) = M,$$

$$\text{but} \quad G(t+1) = \cdots G(t+n) = Z\},$$

where n counts the number of days with $t+n=T$ $(i=1, j+1)$ for $j=$ warm or cold; for the meridional residence time, $L(M)$, Z and M have to be interchanged. The relative frequency distribution of the zonal and meridional residence times are presented in Fig. 3 to demonstrate their different dynamical behaviour, and the ENSO response.

(i) The zonal state is characterized by a higher frequency of short residence times with a peak between 2 and 4 days which is associated with the time scale of synoptic disturbances; the residence time of the meridional state is more evenly distributed with more frequent longer periods (Fig. 3a). The null-hypothesis that both distributions have the same population in common can be rejected on a 95% level (Kolmogoroff–Smirnov test).

(ii) A qualitative difference between warm and cold event distributions can be recognized (Fig. 3b, c). Warm event residence times of the meridional state show a frequency maximum at shorter period lengths (2 to 4 days), whereas longer residence times (8 to 10 days) are dominant in cold episodes; the opposite holds for the zonal regime. The meridional state occupies 69 or 73% of a warm or cold winter season, whereas the complementary time (only 31 or 27% of the winter season) is occupied by zonal regimes. Thus, the response of meridional variability on ENSO forcing (given by its residence time distribution) is most likely to dominate the dynamics of a winter season, even though the zonal state variability may change in an opposing manner.

Winters of warm ENSO extremes (Fig. 2) are associated with an increase of the occurrence of the shorter (2–4 days) residence times of the meridional regimes and a reduction of the longer ones (8–10 days). Accordingly, a mid-latitude transient eddy statistic, which describes the internal variability of the system, will respond to ENSO warm events by spectral variance density peaks in the related frequency domains, i.e., the variance contributions by the shorter periods of 4–8 days (longer periods of 16–20 days) will be enhanced (reduced) in warm event winters, whereas the opposite signal occurs in winter seasons at the end of cold episodes (a residence time signal corresponds to a half-period in terms of a spectral time decomposition). As meridionality is

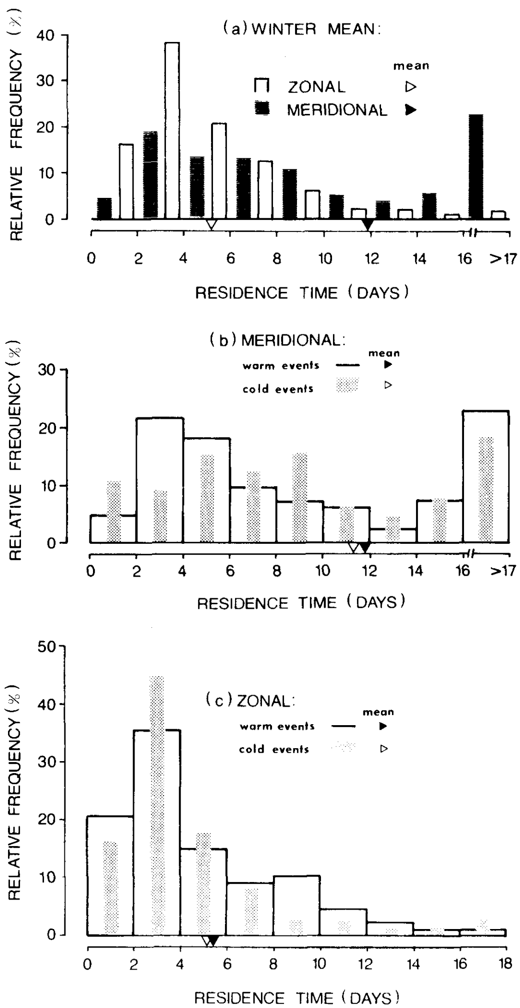

Fig. 3. Relative frequency distribution of the duration of spells (period length or residence time) of the zonal and the meridional circulation state in winter; the mean values are indicated on the abscissa. (a) All winter seasons for both the zonal and the meridional state; the meridional (b) and zonal (c) states for winter seasons at the end of the 19 warm and 17 cold episodes. Note the scale change in the last column of the meridional state. The meridional state occupies 69% (73%) on an average warm (cold) winter, but the zonal state only 31% (27%).

associated with higher zonal wavenumbers, the enhanced warm event variance contributions at shorter periods will be observed at smaller wavelengths. These phenomenological results are in agreement with wavenumber-frequency spectra of mid-latitude transient eddies composed around

ENSO warm and cold events (Hansen et al., 1989; see also Fraedrich and Böttger, 1978; Mechoso et al., 1987); they show that warm event winter seasons tend to be accompanied by a strong peak at wavenumber 7 and period 5 days.

4. Discussion

The signature of the tropical Pacific boundary forcing due to warm and cold ENSO extremes in the mid-latitudes has been investigated by an analysis of a daily catalogue of 36 individual hemispheric circulation patterns which are composed of a bimodal (zonal/meridional) circulation state characterizing the extratropical Northern Hemisphere. The rank statistics of the number of days per season spent in one of these modes exhibits the largest response of enhanced (reduced) zonality in the winters which follow the year of the warm (cold) event; the individual circulation patterns show that this change in the steering of the synoptic disturbances modifies predominantly the cross Pacific storm track direction, in particular its more sensitive tail in the eastern part, which is shifted southward during warm episodes. Furthermore, the shorter (longer) period fluctuations are enhanced in warm (cold) event winters. It may be concluded that such a traditional synoptic climatology can lead (even today) to a meaningful description, not only of secular trends in weather regimes (Dzerdzeevskii, 1962, 1971, Fig. 3) but also of the extratropical circulation response to changing boundary conditions as they are forced by the equatorial Pacific sea surface temperatures. Note the agreement with analyses of GCM ENSO response experiments, which is not only qualitative: Held et al. (1989) document a southward shift of the North Pacific storm track in warm event winters; Palmer and Mansfield (1986a, b) show two modes of warm event responses over North America; Mechoso et al. (1987) find an enhanced warm event period of 5 days and wavenumber 7 response in the mid-latitude wavenumber-frequency spectra.

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REFERENCES

Baur, F. 1951. Extended range weather forecasting. In: *Compendium of meteorology.* (ed. T. F. Malone), American Meteorological Society, Boston, 811–833.

Dzerdzeevskii, B. L. 1962. Fluctuations of climate and the general circulation of the atmosphere in extra-tropical latitudes of the Northern Hemisphere and some problems of dynamic climatology. *Tellus 14*, 328–336.

Dzerdzeevskii, B. L. 1971. Long-term fluctuations of the general circulation of the atmosphere and of the climate and the major regularities of planetary circulation. In: *General circulation of the atmosphere*; (eds. B. L. Dzerdzeevskii and Kh. P. Pogosyan), Israel Program of Scientific Translations, Jerusalem, 283–303.

Dzerdzeevskii, B. L. 1975. *The observed circulation of the atmosphere and climate* (in Russian). Moskwa, 285 pp.

Fraedrich, K. 1988. El Niño/Southern Oscillation predictability. *Mon. Wea. Rev. 116*, 1001–1012.

Fraedrich, K. 1990. European Grosswetter during the warm and cold extremes of the El Niño/Southern Oscillation. *Intern. J. Climatol. 10*, 21–32.

Fraedrich, K. and Böttger, H. 1978. A wavenumber-frequency analysis of the 500 mb geopotential at 50° N. *J. Atmos. Sci. 35*, 745–750.

Geisler, J. E., Blackmon, M. L., Bates, G. T. and Munoz, S. 1985. Sensitivity of January climate response to the magnitude and position of equatorial Pacific sea surface temperature anomalies. *J. Atmos. Sci. 42*, 1037–1049.

Hamilton, K. 1988. A detailed examination of the extratropical response to tropical El Niño/Southern Oscillation events. *J. Climatol. 8*, 67–86.

Hansen, A. R., Sutera, A. and Venne, D. E. 1989. An examination of mid-latitude power spectra: evidence for standing variance and the signature of El Niño. *Tellus 41A*, 371–384.

Held, J. M., Lyons, S. W. and Nigam, S. 1989. Transients and the extratropical response to El Niño. *J. Atmos. Sci. 46*, 163–174.

Hess, P. and Brezowsky, H. 1977. Katalog der Grosswetterlagen. *Ber. Dtsch. Wetterdienst* (Offenbach) 113, Bd. 15, 39 pp.

Horel, J. D. and Wallace, J. M. 1981. Planetary-scale atmospheric phenomena associated with the Southern Oscillation. *Mon. Wea. Rev. 109*, 813–829.

Mechoso, C. R., Kitoh, A., Moorthi, S. and Arakawa, A. 1987. Numerical simulations of the atmospheric response to a sea surface temperature anomaly over the equatorial eastern Pacific Ocean. *Mon. Wea. Rev. 115*, 2936–2956.

Namias, J. and Cayan, D. R. 1984. El Niño: Implications for forecasting. *Oceanus 27*, 41–47.

Olberg, M. 1977. The distribution law of the periods of the Dzerdzeevskij types of zonal and meridional circulation. *Idöjaras 81*, 193–201.

Palmer, T. N. and Mansfield, D. A. 1986a. A study of winter-time circulation anomalies during past El Niño events using a high resolution general circulation model. I: Influence of model climatology. *Quart. J. R. Met. Soc. 112*, 613–638.

Palmer, T. N. and Mansfield, D. A. 1986b. A study of winter-time circulation anomalies during past El Niño events, using a high resolution general circulation model. II. Variability of the seasonal mean response. *Quart. J. R. Met. Soc. 112*, 947–975.

Rasmusson, E. M. and Carpenter, T. H. 1983. The relationship between eastern equatorial Pacific sea surface temperatures and rainfall over India and Sri Lanka. *Mon. Wea. Rev. 111*, 517–528.

Ropelewski, C. F. and Halpert, M. S. 1986. North American precipitation and temperature patterns associated with the El Niño/Southern Oscillation (ENSO). *Mon. Wea. Rev. 114*, 2352–2362.

van Loon, H. and Madden, R. A. 1981. The Southern Oscillation. Part I: Global associations with pressure and temperature in northern winter. *Mon. Wea. Rev. 109*, 1150–1162.

van Loon, H. and Rogers, J. C. 1981. The Southern Oscillation. Part II: Associations with changes in the middle troposphere in the northern winter. *Mon. Wea. Rev. 109*, 1163–1168.

van Loon, H. and Shea, D. J. 1985. The Southern Oscillation. Part IV: The precursors south of 15°S to the extremes of the Oscillation. *Mon. Wea. Rev. 113*, 2063–2074.

Wallace, J. M. and Jiang, Q. 1987. On the observed structure of the interannual variability of the atmosphere/ocean climate system. In: *Atmospheric and oceanic variability* (ed. H. Cattle), Royal Meteorological Society, Bracknell, 17–43.