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THE NATURAL HISTORY OF THE SLAPTON LEY NATIONAL NATURE RESERVE XXIII: THE CLIMATE OF SLAPTON LEY

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Abstract

Meteorological observations have been carried out at Slapton Ley Field Centre since April 1960; this paper reviews the first four decades of that record. The ecological richness of the Slapton Ley National Nature Reserve relates in large part to its climate, which is very favourable by British standards: mild and wet with few frosts and minimal snowfall. Since 1960, the Slapton climate has become noticeably warmer, especially in winter. Rainfall has tended to be more strongly seasonal in its distribution, with a tendency towards wetter winters and drier summers; there have been some major droughts, the one in 1975-76 being the most extreme and protracted. A number of the observed changes in climate, with the exception of rainfall, can be related to a strengthening of the westerly circulation in the North Atlantic since 1960.

Introduction

Slapton Ley, a freshwater lagoon separated from the sea by a shingle ridge, lies close to the most southerly point in Devon. Slapton Ley Field Centre is located on the eastern edge of the village of Slapton, less than a kilometre from the Ley and Start Bay. Given its coastal location on the southern flank of the south-west peninsula, it is hardly surprising that Slapton enjoys a mild, moist climate. Indeed, the epithet, *A Fortunate Place* (Staines, 1983), applies to the climate of the area above all else!

A climatological station was set up with the assistance of the Meteorological Office in the spring of 1960, within a few months of the establishment of the Field Centre itself. This paper updates Ratsey (1975) who analysed the first thirteen years of data collected at the station. With nearly forty years of records now available, a longer term perspective can be taken. Moreover, issues like global warming and drought were not apparent in the early 1970s and it is now possible to place the Slapton meteorological records within regional, national and even global context.

The Slapton weather station is located to the north east of the Field Centre at an altitude of 32 m. O.D. The site is reasonably well exposed except to the south west where trees and buildings have encroached more closely than is ideal. The analyses presented here are based on a computerised record of the daily observations provided to the Field Centre by the Meteorological Office. Analyses have used Excel™ spreadsheets, except where indicated. Except where stated, analyses are for the complete calendar years 1961 to 1997 inclusive.

Temperature

Table 1 summarises average temperatures at Slapton since January 1961. Oceanic influence is immediately apparent in the mean annual temperature of 10.7 °C, almost as high as anywhere on mainland Britain (Tout, 1976). As expected, given strong oceanic influence,

TABLE 1. Average temperatures at Slapton Ley Field Centre, 1961-1997

	Mean maximum temperature (°C)	Mean minimum temperature (°C)	Mean air temperature (MAT) (°C)	Standard deviation (MAT) (°C)	Coefficient of variation (MAT) (%)
January	8.7	3.6	6.1	1.6	26.1
February	8.6	3.3	5.9	1.8	29.4
March	10.3	4.2	7.2	1.1	16.1
April	12.3	5.4	8.9	0.8	9.2
May	15.2	8.0	11.4	1.1	10.2
June	18.2	10.5	14.3	0.9	6.5
July	20.2	12.4	16.3	1.1	6.7
August	20.1	12.6	16.3	1.1	6.9
September	18.0	11.1	14.5	0.8	5.8
October	14.9	9.2	12.0	1.2	10.2
November	11.5	6.1	8.8	1.1	12.7
December	9.6	4.4	7.0	1.2	16.5
Year	**13.9**	**7.6**	**10.7**	**0.5**	**5.0**

there is a small annual range of mean monthly temperature (10.4 °C) compared to more continental locations to the east (*e.g.* 13.7 °C at Heathrow: Tout, 1976). July and August are equally warm, and the coldest month is February. The relative lateness of these extremes is typical for a maritime location: at Kew the maximum and minimum are July and January respectively (Tout, 1976). As indicated by the coefficient of variation, temperatures are least predictable in the winter half of the year, most especially in January and February when anticyclonic conditions with winds from an easterly quarter can introduce much colder polar continental weather than is normal. Nevertheless, a mean air temperature for February of 5.9 °C indicates that, on average, grass can continue to grow throughout the year (a threshold of 6 °C is usually taken to be the lower limit for grass growth). Low coefficients of variation from June to September indicate the dominance of tropical maritime air masses in summer.

The strength of the maritime influence is underlined by data given in Table 2; these confirm an equable climate, lacking extremes in either direction. On average, only 17 air frosts occur each year, limited to the period November through April; this compares with 5 in Scilly (Tout, 1976) and 49 at Oxford* . Only one air frost has occurred in May and none during the period June to October inclusive. Most air frosts occurred in 1963 (40), with other notable years being 1965 (33), 1969 (35), 1970 (30), 1979 (31) and 1985 (35). Since 1987 only one year has recorded more than 20 air frosts, 1996 (28), a sign of generally mild winters in recent years. In 37 years, daytime temperatures have remained below zero only 47 times. These occasions are actually confined to ten individual years with only 1963 (4), 1970 (22) and 1980 (10) recording more than a single instance. There are, on average, 58 ground frosts per year, the same number as at Clacton (Mayes & Sutton, 1997); naturally there are more ground frosts at an inland location like Oxford (104). Only one ground frost has been recorded at Slapton in June and September and none in either July or August. At

* One of the authors (TPB) was Director of the Radcliffe Meteorological Station at Oxford University from 1986 to 1996. Data given here are taken from the unpublished records of the Station.

TABLE 2. The occurrence of air temperatures below 0 °C and above 20 °C and 25 °C at Slapton Ley Field Centre, 1961-1997

	Average number of days with air minimum below 0°C	Total number of days with air maximum below 0°C	Total number of days with air maximum above 25°C	Average number of days with air maximum above 20°C	Average number of days with grass minimum below 0°C
January	5	22	0	0	13
February	4	11	0	0	11
March	3	13	0	0	10
April	1	0	0	0	5
May	0	0	0	1	1
June	0	0	16	7	0
July	0	0	44	16	0
August	0	0	27	15	0
September	0	0	0	4	0
October	0	0	0	0	1
November	1	0	0	0	7
December	3	1	0	0	10
Year	**17**	**47**	**87**	**43**	**58**

the other end of the scale, there have been only 87 days when the maximum temperature has exceeded 25 °C, but on only one occasion (28 June 1976) has the maximum exceeded 30 °C (30.5 °C). This is in clear contrast to an inland location like Oxford where 19 days exceed 25 °C each year on average and 2 days exceed 30 °C; the maximum temperature recorded at Oxford is 35.1 °C. At Slapton about half the days in July and August exceed 20 °C but there is a small range of temperature in these months with a modest mean maximum temperature but a relatively high mean minimum temperature (Table 1). The lowest temperature recorded at Slapton is -8 °C on 13 January 1987 (Table 3) compared to an absolute minimum at Oxford of -16.6 °C.

TABLE 3. Extreme air temperatures recorded at Slapton Ley Field Centre, 1961-1997

	Lowest maximum (°C)	Highest maximum (°C)	Lowest minimum (°C)	Highest minimum (°C)
January	-3.5 (1987)	14.4 (1969)	-8.0 (1987)	11.3 (1983)
February	-1.3 (1991)	14.4 (1971)	-6.8 (1991)	10.5 (1989)
March	1.7 (1964)	17.2 (1993)	-6.5 (1986)	11.1 (1990)
April	4.0 (1981)	20.5 (1982)	-2.5 (1978)	11.8 (1984)
May	7.5 (1996)	24.1 (1988)	-0.1 (1979)	15.5 (1989)
June	11.7 (1964)	30.5 (1976)	2.6 (1987)	21.2 (1976)
July	14.0 (1988)	28.0 (1984)	6.2 (1993)	19.8 (1976)
August	12.8 (1962)	28.5 (1990)	6.1 (1964)	20.0 (1995)
September	9.9 (1986)	24.1 (1961)	4.2 (1979)	17.5 (1991)
October	7.6 (1992)	23.4 (1997)	0.2 (1983)	16.1 (1961)
November	3.9 (1969)	17.1 (1978)	-2.2 (1969)	14.0 (1996)
December	-0.3 (1978)	15.4 (1985)	-4.5 (1981)	12.3 (1985)

TABLE 4. Mean air temperatures recorded at Slapton Ley Field Centre by decade

Decade	Winter	Spring	Summer	Autumn	Annual
(a) Mean air temperature °C					
1960s	5.8	9.0	15.2	11.7	10.4
1970s	6.5	9.0	15.7	11.8	10.8
1980s	6.3	8.9	15.8	11.8	10.7
1990s	6.8	9.7	16.0	11.9	11.1
(b) Mean maximum air temperature °C					
1960s	8.3	12.2	18.9	14.6	13.5
1970s	9.1	12.4	19.6	14.9	14.0
1980s	8.9	12.5	19.7	14.6	13.9
1990s	9.4	13.2	19.9	15.1	14.4
(c) Mean minimum air temperature °C					
1960s	3.3	5.8	11.6	8.8	7.4
1970s	3.9	5.6	11.9	8.6	7.5
1980s	3.6	5.7	11.9	8.9	7.5
1990s	4.1	6.3	12.1	8.9	7.8

Table 4 shows mean air temperatures by decade for the years 1961 to 1997. Compared to the 1960s, the 1970s were considerably warmer, 0.4 °C on average, a large amount given a standard deviation for annual mean air temperature of only 0.5 °C (Table 1). The 1980s were if anything slightly cooler than the 1970s, but the 1990s have seen renewed warming. Table 4a shows that the warming has been unequally distributed through the year: the 1970s warming involved increases in winter and summer, while the 1990s warming has been in winter and spring. Overall, therefore, the largest effect has been seen in the winter months with some very warm winters in recent years and a notable decrease in the number of air frosts, as mentioned above. Both maximum and minimum temperatures have increased by much the same amount during this time (Tables 4b and 4c); the warming is not just confined to daytime or night-time therefore.

The coldest winter on record is easily l963 (3.0 °C), followed by 1965 (5.0 °C). The warmest winter on record is 1990 (8.4 °C), followed by 1975 (8.3 °C), 1995 and 1989 (both 8.1 °C). The coldest summer was 1972 (14.3 °C), followed by 1962 and 1963 (both 14.5 °C). The warmest summer was easily 1976 (18.0 °C), followed by 1983 (17.4 °C), 1995

TABLE 5. The coldest and warmest years and seasons recorded at Slapton Ley Field Centre (1961-1997) ranked from 1, the coldest, to 37, the warmest

Rank	Year	Winter	Spring	Summer	Autumn
1	9.6 1963	3.0 1963	7.6 1962	14.3 1972	10.4 1993
2	9.7 1986	5.0 1965	7.8 1986	14.5 1962	10.4 1974
3	9.8 1962	5.0 1979	8.0 1988	14.5 1963	11.0 1992
35	11.7 1990	8.1 1995	10.3 1992	17.3 1995	12.8 1989
36	11.7 1995	8.3 1975	10.3 1961	17.4 1983	12.9 1997
37	11.8 1989	8.4 1990	10.6 1990	18.0 1976	12.9 1995

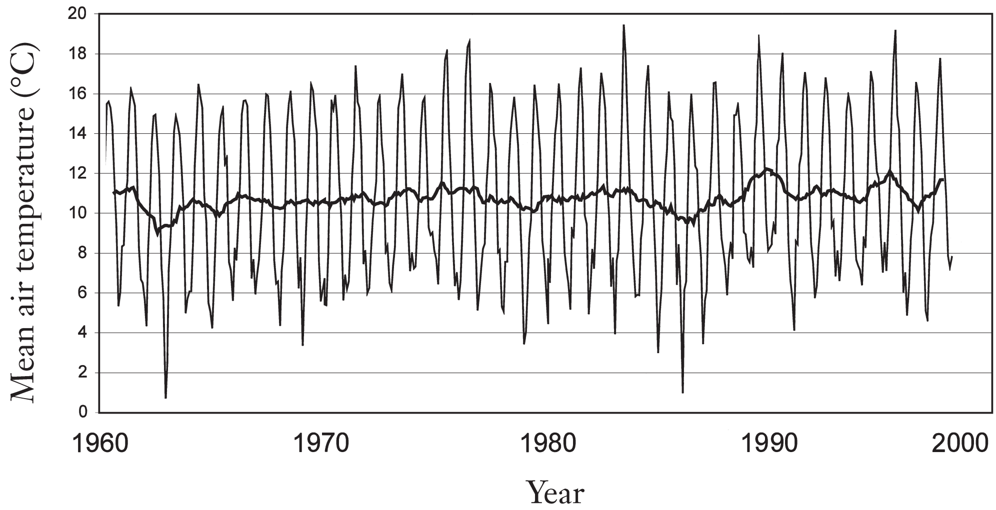

FIG. 1. Monthly mean temperature (°C) for the study period together with a 12-month weighted running mean.

(17.3 °C), 1975 (17.2 °C) and 1989 (17.0 °C). As it happens, hot summers at Slapton tend to be dry too, a matter that will be further discussed in the next section.

Table 5 lists, for complete years and individual seasons, the three warmest and three coldest years on record. The warmest calendar year was 1989 followed by 1995 and 1990, reflecting the extreme warmth of the last decade. A 12-month weighted running mean shows that the warmest 12-month period actually centres on the period October to December 1989 when the mean temperature was 12.2 °C, exactly three standard deviations above the long-term mean (Table 1). The coldest period centres on August and September 1962 when the mean temperature was only 9.1 °C, reflecting the very cold winter of 1963. Fig. 1 shows monthly mean temperatures together with the running mean for the entire period of observation.

Despite clear evidence of significant warming over these four decades (Table 4), this is hard to detect against the strong seasonal cycle, emphasising how small the warming trend has been. The mean temperature in the 1990s (11.1 °C) is, after all, only 0.4 °C above the long-term mean. It can take many years for weak signals to be detected within a noisy record such as air temperature; long-term climate monitoring must therefore be maintained over many years if such subtle effects are to be identified with confidence (Burt, 1994).

PRECIPITATION

The first complete calendar year of rainfall data at Slapton is for 1961 so the statistics discussed here relate to the period 1961-1998 inclusive. The average annual precipitation for this period is 1059.1 mm, a little wetter than most coastal locations in south-west England (Perry, 1997, figure 2.3), perhaps reflecting the nearby influence of Dartmoor. Table 6 gives mean monthly rainfall and the mean number of rain days (at least 0.1 mm recorded).

TABLE 6. Mean monthly rainfall (mm) statistics for Slapton Ley Field Centre, 1961-1988

Month	Total rainfall	Standard deviation	Coefficient of variation	Number of rain days	Rainfall per rain day
January	124.9	63.1	49.1	18	6.8
February	98.4	60.6	61.6	15	6.8
March	90.2	43.0	47.7	15	6.0
April	63.5	35.4	55.8	13	4.9
May	64.5	36.6	56.8	12	5.2
June	60.4	41.7	68.9	11	5.5
July	60.9	33.6	55.1	10	6.2
August	73.3	35.9	49.0	12	6.2
September	79.0	44.0	55.7	12	6.3
October	97.5	49.9	51.2	15	6.7
November	119.1	60.4	50.7	17	7.0
December	129.0	61.7	47.8	17	7.4
Year	**1059.1**	**167.2**	**15.8**	**167**	**6.4**

The number of rain days is lower than for many places on the south-west peninsula, with rain recorded on only 46% of days, compared to the usual figure of around 60% in Cornwall (Dancey, 1981). Only 42% of the rain days occur in the summer half-year (April-September) and this is reflected in the lower totals for these months, especially in late spring and early summer. Only 37.9% of the annual rainfall is received in the summer half-year and the average amount of rain per rain day is lowest at this time, especially in the period April to June. In contrast, 62.1% of the annual rainfall is received in the winter half-year with November, December and January recording the highest totals. The average amount of rain per rain day is highest in these months too. There is no clear pattern of rainfall variability within the year, but it is notable that the wet months December and January have low coefficients of variation. June, on the other hand, is both the driest month and the most variable. Very dry Junes have been associated with drought years, most notably the two driest Junes on record, 1975 and 1976, with only 3.3 and 5.5 mm respectively. June l984 (9.1 mm) and June 1995 (12.8 mm), which were also drought years (see next paragraph), come 4th and 5th in rank order. At the other end of the scale the total for June 1968 was 159.7 mm, wetter than eleven entire summers! It may therefore be that June is a particularly important marker with respect to the onset of summer drought in the Slapton region.

Fig. 2 shows monthly rainfall totals at Slapton since April 1960, together with a 12-month running mean. Fig. 3 shows annual (calendar year) rainfall totals from 1961 to 1998 together with a 5-year running mean. Both graphs show well the various wet and dry spells that have occurred at Slapton over the last four decades. The mid 1960s were a time of higher than average rainfall while the first half of the 1970s were dry, culminating in the exceptional drought of 1975-76. The 12-month total of 561 mm from September 1975 to August 1976 is easily the lowest 'yearly' total on record, barely half the long-term average. Since then, other major droughts have happened, though none have been as extreme as in 1975-76: some, like 1975-76, have comprised a dry winter between two dry summers; others have tended to relate solely to a very dry summer. There has been a tendency for

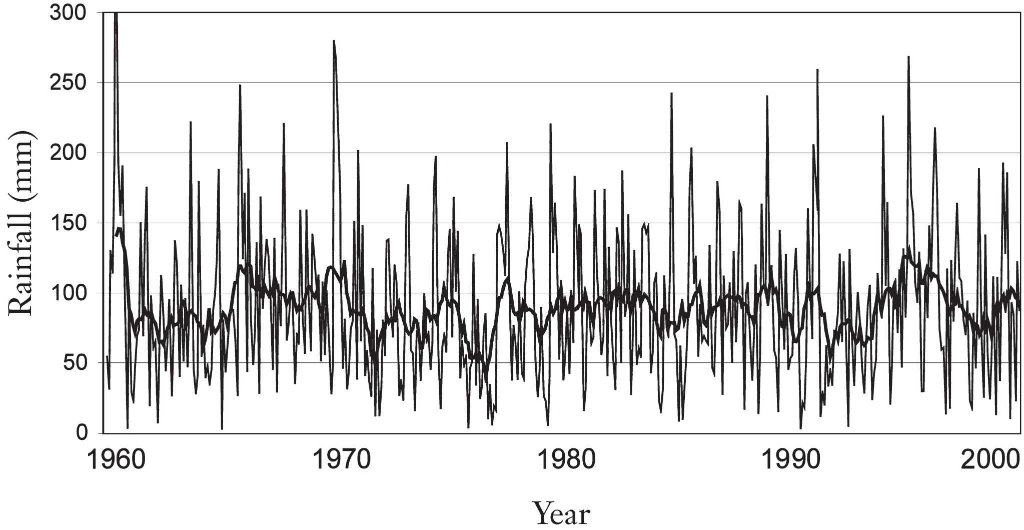

FIG. 2. Monthly rainfall totals (mm) for the study period together with a 12-month weighted running mean.

annual rainfall to increase since the late 1980s. This may relate to the strengthening of the westerly circulation over the North Atlantic. In Scotland, this increase has been dramatic and sustained (Werritty, pers. comm.), whereas at Slapton rainfall totals had reached a plateau by the mid-1990s. Overall, the rainfall record at Slapton follows changes in atmospheric circulation less closely than does temperature; this will be discussed in more detail in the final section.

Table 7 shows a variety of rainfall totals in ascending rank order (driest period ranks 1). True summer rainfall (June-August) is lowest in 1976 but the summers of 1983, 1989 and 1984 also show up as extremely dry. The summers of 1990 and 1995 were particularly hot as well as dry; of course, droughts are not just a question of rainfall deficit and the

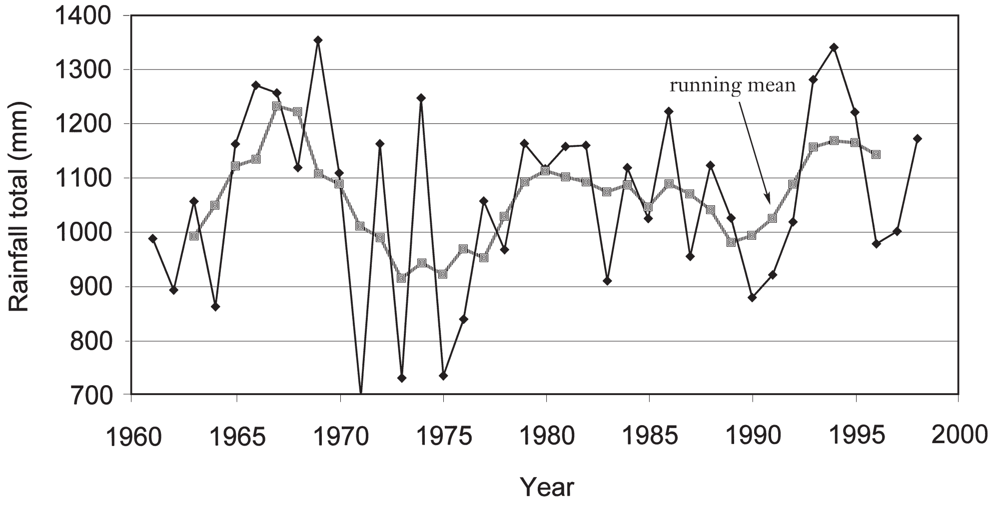

FIG.3. Annual rainfall totals for the calendar years 1961 to 1998 together with a 5-year running mean.

TABLE 7. Top-ten ranking of various rainfall totals and the winter: summer rainfall ratio (see text for details). Ranks in ascending order

Rank	June to August	April to September	April to next September	DJF:JJA ratio
1	1976 (41.1 mm)	1990 (220.7 mm)	1976 (907.1 mm)	1983 (4.83)
2	1983 (68.9 mm)	1976 (228.1 mm)	1991 (1145.5 mm)	1990 (4.47)
3	1989 (95.5 mm)	1984 (255.3 mm)	1972 (1201.4 mm)	1984 (4.45)
4	1984 (96.6 mm)	1978 (261.4 mm)	1992 (1211.9 mm)	1995 (3.83)
5	1975 (100.7 mm)	1971 (280.4 mm)	1997 (1250.9 mm)	1994 (3.42)
6	1964 (123.5 mm)	1964 (302.5 mm)	1984 (1296.0 mm)	1976 (3.19)
7	1996 (124.6 mm)	1975 (332.1 mm)	1963 (1299.3 mm)	1961 (3.06)
8	1990 (139.2 mm)	1996 (332.9 mm)	1971 (1301.9 mm)	1996 (3.06)
9	1961 (142.4 mm)	1997 (349.0 mm)	1989 (1305.5 mm)	1975 (2.83)
10	1995 (146.2 mm)	1961 (349.8 mm)	1965 (1315.5 mm)	1979 (2.80)

combination of low rainfall and hot weather produces a more extreme drought than rainfall figures alone might suggest. In fact, 1990 ranks first on the summer half-year figures (April-September) but 1995 does not figure in the top ten list (ranking 18th driest in 38 years). Further north, the 1995 summer produced extreme drought conditions, for example in the northern Pennines (Burt *et al.*, 1998). One distinctive feature of British rainfall in the 1990s has been the great contrast between wet winters and dry summers. Using the ratio between rainfall in winter (December-February: DJF) and summer (June-August: JJA), Jones & Conway (1997) noted a recent trend towards wetter winters and the highly unusual nature of the winter: summer rainfall ratio in 1995. At Slapton, l995 ranks only fourth in terms of the DJF:JJA ratio, but the tendency towards an increased seasonal contrast in the 1990s is clearly evident.

Phillips & McGregor (1998) used a drought severity index*, based on accumulated monthly precipitation deficits and with three-monthly and six monthly initiation rules, for assessing the variability in timing and the severity of the drought hazard for four locations in Devon and Cornwall (St Mawgan, Princetown, Chivenor and Culdrose) since 1957. We have repeated their analysis for the Slapton Ley rainfall data, but since the two graphs look quite similar, only results for the six month index are given here (Fig. 4). The three-month index (DSI_3) identifies more droughts, as expected, and includes briefer droughts where a dry summer follows a wet winter. The six-month index (DSI_6) identifies the more persistent and severe droughts better, though many short droughts show up too. Phillips & McGregor (1998) identified seven droughts which occurred throughout the south-west

*Phillips & McGregor (1998, page 361) describe the calculation of the three month drought severity index (DSI_3) as follows. "Consider the rainfall anomaly in month t, denoted X_t. If X_t is negative (i.e. below its mean level) and rainfall in the three-month period, X_t X_{t-1}, X_{t-2}, is lower than the three-monthly mean, then initiate a drought sequence in month t, assigning DSI_3 a positive value that is equal to the precipitation deficit in month t. Now consider the month t + 1. Suppose the rainfall anomalies in months t and t + 1 were -X and -Y mm respectively, then DSI_3 for month t + 1 equals X + Y, if and only if the three month mean total for the months t - 1, t and t + 1 has not been exceeded. If the rainfall anomaly is positive in month t + 1, then a drought can continue, with DSI_3 = X - Y, provided that the three-monthly mean total has not been exceeded. All drought sequences are terminated immediately when this three-month mean total has been exceeded and DSI_3 is assigned a value of zero." The index is standardised by dividing the absolute deficit by the station's mean annual rainfall and then multiplying by 100, this allows inter-station comparison.

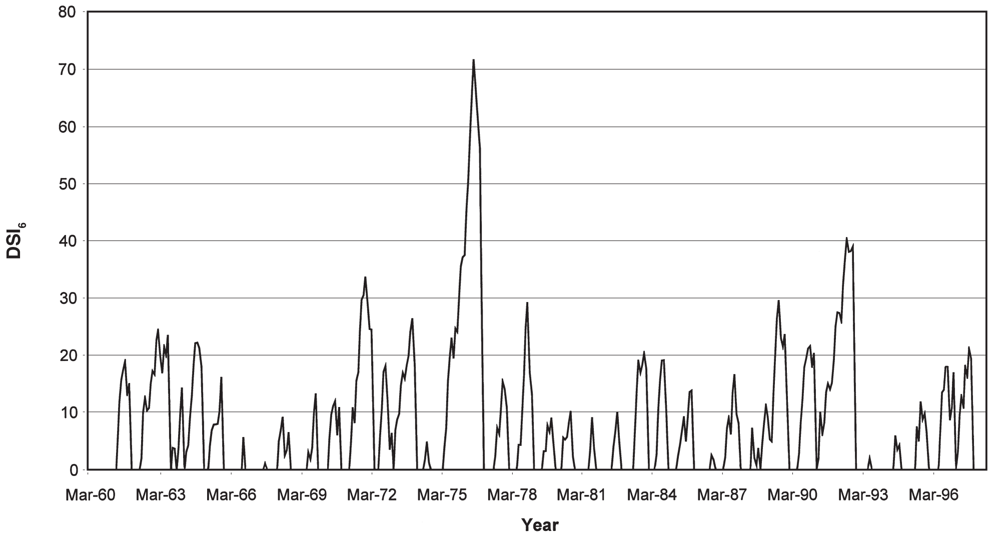

FIG. 4. Six-month Drought Severity Index (DSI_6) for the study period, using the method of Phillips & McGregor (1998)

peninsula (1962-3, 1964-5, 1975-6, 1978, 1983-4, 1992 and 1995-7) which are all evident in the Slapton record. In addition to these, significant droughts appear in the Slapton record for 1971-2, 1989 and 1990. The most extreme and protracted drought is clearly that of 1975-76. The drought of 1995-7, which was protracted in central and north Devon, does not appear so severe at Slapton. This may be an artefact of the calculation in that any drought sequence is terminated immediately the mean total has been exceeded and the index returns to zero. At Slapton (as at St Mawgan), there was clearly sufficient rainfall in some winter months to reset the index each year so that a persistent drought did not accumulate on the index scale.

Observations of 'snow lying' are available only from 1971 which means that the very cold winter of 1962/63 and the winter of 1969/70, which Ratsey (1975) also mentions in relation to snowfall, are excluded from our analysis. On average there is snow lying at 09.00 GMT on six mornings each year at Slapton, four in winter and two in spring. No snow lying has been recorded between June and October, and only very occasionally in May and November. Totals vary greatly between years and, usually, the annual total is very low. In three years (1977, 1988, 1992), there has been no snow lying at all, and in 21 of 27 years, there have been eight or fewer days with snow observed. The years with most snow lying on record are 1978 (13), 1986 (13), 1985 (15) and 1979 (19).

WIND SPEED AND DIRECTION

Observations of wind speed have been made in two ways at Slapton. From April 1960, observers have estimated wind speed at 0900 hours GMT using the Beaufort Scale (Meteorological Office, 1982). Run of wind has also been recorded daily using a standard Meteorological Office cup anemometer since the 1970s but we include no analysis of this shorter record here. Occasionally anemographs have been installed as part of specific research projects (*e.g.* Job, 1987), but no long-term analysis of such records has been possible.

Table 8. Mean wind speed (knots) recorded at Slapton Ley Field Centre 1961-1997. Observations made at 0900 GMT on the Beaufort Scale

Month	mean	minimum	year	maximum	year
January	9.5	4.9	1989	19.0	1996
February	9.1	4.5	1992	15.4	1986
March	9.0	3.0	1997	14.5	1972
April	9.2	3.9	1991	20.1	1972
May	9.6	2.5	1991	21.4	1972
June	8.5	4.3	1984	15.0	1972
July	8.2	3.7	1991	15.4	1977
August	8.8	3.7	1991	19.2	1974
September	8.9	5.0	1991	14.8	1974
October	8.8	4.6	1969	13.8	1961
November	8.7	3.3	1990	15.3	1980
December	9.9	4.4	1984	16.6	1961
Winter	*9.5*	*6.2*	*1991*	*13.3*	*1962*
Spring	*9.3*	*4.0*	*1991*	*18.7*	*1972*
Summer	*8.5*	*4.5*	*1991*	*14.7*	*1972*
Autumn	*8.8*	*4.5*	*1990*	*12.3*	*1961*
Annual	**9.0**	**4.9**	**1991**	**13.7**	**1972**

Table 8 lists mean monthly wind speeds for the study period. The speeds are lower and the annual cycle is much more subdued than for nearby coastal stations listed by Shellard (1976, Table 3.6). This may either reflect the protected site of the weather station or, more likely, the sheltered location of Slapton village on the east-facing Start Bay. It is perhaps surprising that spring is the second windiest season and May the second windiest month.

Table 9 lists wind speeds in four classes: these correspond to Beaufort Forces 0-1, 2-3, 4-5, and greater than 5 respectively. Six directional classes are provided to allow an equal number of 'directions' in each class (since wind direction is recorded only to the nearest ten degrees). As expected, westerly winds occur most often, particularly at lower speeds. In the highest class (Force 6 and above), strong winds are common from the east as well as from the west and south-west; strong easterlies are important for beach erosion on Slapton Sands since the beach faces due east (Job, 1987). Nearly half the observations of wind speed fall within the 4-10 kt class (Force 2-3) with just over one quarter of observations in the 11-21 kt class. On the Isles of Scilly (Shellard, 1976, Table 3.2), wind speeds are of course much higher, given greater exposure: in relation to the right-hand column of Table 9, the

Table 9. Frequency distribution of wind speed (knots) in six wind direction classes recorded at Slapton Ley Field Centre 1961-1997. Observations made at 0900 GMT on the Beaufort Scale

Speed \ Direction	010°-060°	070°-120°	130°-180°	190°-240°	250°-300°	310°-360°	overall
< 3 kts	2.6	2.3	2.0	2.9	6.0	4.1	20.0%
4-10 kts	6.7	7.9	4.0	7.2	13.6	7.1	46.5%
11-21 kts	4.2	5.7	2.1	5.4	6.6	2.2	26.3%
> 22 kts	0.9	1.7	0.6	1.8	1.8	0.4	7.2%
Total	**14.4**	**17.6**	**8.7**	**17.4**	**28.0**	**13.9**	**100.0%**

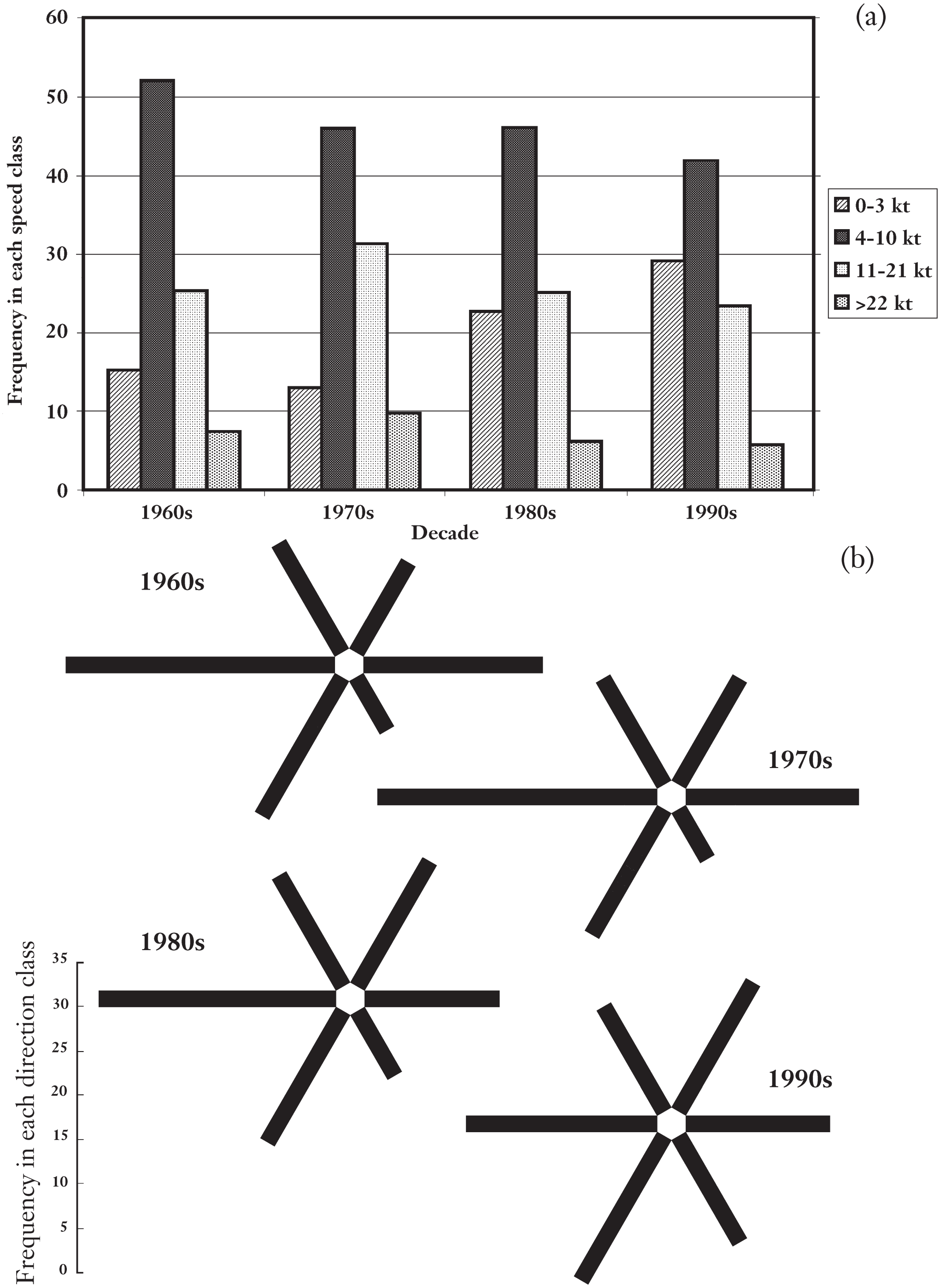

FIG. 5. Observations of wind speed and direction at 09.00 hours G.M.T. by decade: (a) the frequency of wind speed (knots) in four speed classes; (b) the frequency of wind direction in six directional classes. Wind direction classes in 60-degree segments.

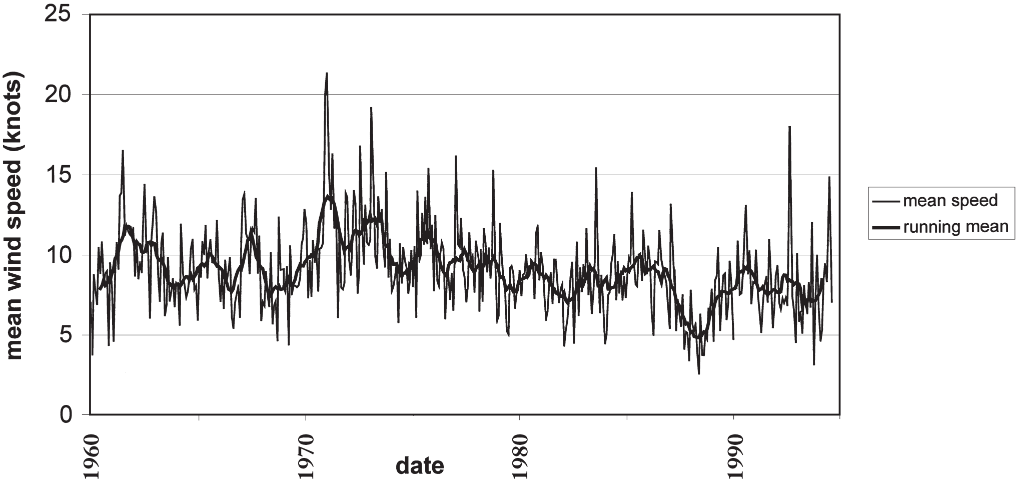

FIG. 6. Monthly mean wind speed (kt) for the study period together with a 12-month weighted running mean.

corresponding percentages are 0-3 kt - 11.4%, 4-10 kt - 31.3%, 11-21 kt - 44.4%, and > 22 kt - 12.9% . Fig. 5 shows the frequency of wind speeds and directions by decade. The 1970s showed a decrease in the percentage of wind speeds in the 4-10 kt class and an increase in the 11-21 kt class. Thereafter, mean wind speeds have fallen with an increase in the percentage within the lowest category, 0-3 kt. In terms of directional changes, the general decrease in speeds has been accompanied by a decrease in the fraction of westerly winds (250-300° class) with an increase in more southerly winds, especially in the 130-180° category. There has also been a decrease in easterly winds (which tend to be relatively strong) and an increase in lighter north-easterlies.

Mean monthly wind speed, together with a 12-month running mean, are plotted in Fig. 6. Wind speeds in the 1960s fluctuated around the long-term average, but the early 1970s were a time of high winds. Since then, wind speed has declined steadily, with the early 1990s being a time of especially low wind speed compared to the mean.

SUNSHINE, VISIBILITY AND CLOUD COVER

The duration of bright sunshine has been measured at Slapton since August 1986 using a Campbell-Stokes recorder. A glass sphere is used to focus the sun's rays on to a specially treated card. If the solar intensity is sufficient to burn the card, the sun is said to be 'shining'. The record is too short to provide reliable long-term averages, and the lack of data from one month, June 1995, is unfortunate given the hot summer weather that year; the stated June average may therefore be an underestimate rather than a true reflection of cloudier conditions.

Collingborne (1976) includes maps of average (1941-70) daily bright sunshine for the British Isles for March, June, September and December, and for the year as a whole. The figures for Slapton given in Table 10 are very close to the map values for June, September and the annual average, but not for March (3.6 compared to >4) or December (1.3 compared to >2). It is not clear why this discrepancy exists: either winters have become less sunny in recent years, or Slapton has less winter sunshine than nearby coastal resorts*.

TABLE 10. Hours of bright sunshine at Slapton Ley, August 1986 to January 1998 compared to the average total number of hours at Oxford since 1881

	Average total hours	Average hours per day	Most sunshine (hours)	Year	Least sunshine (hours)	Year	Oxford average (hours)
January	50.3	1.7	2.6	1988	0.6	1996	53.5
February	77.0	3.2	4.0	1988	1.5	1993	68.9
March	110.5	3.6	5.1	1990	2.5	1994	112.9
April	176.0	5.9	8.7	1997	4.1	1993	151.2
May	230.2	7.4	10.7	1989	4.8	1994	191.5
June	198.5	6.8	9.0	1994 & 1996	4.3	1990	196.4
July	222.2	7.2	9.9	1989	5.0	1992	190.0
August	206.3	6.7	9.5	1989	4.7	1992	177.6
September	155.3	5.2	7.1	1990	3.8	1994	138.7
October	102.6	3.3	4.0	1993 & 1994	2.7	1990	101.0
November	71.5	2.4	3.3	1996	1.0	1994	63.8
December	41.3	1.3	2.4	1997	0.7	1995	48.3
Winter	168.6	1.9	2.5	1988	1.3	1993	170.7
Spring	516.7	5.6	7.5	1990	4.3	1993	455.6
Summer	626.9	6.9	9.2	1989	5.8	1997	564.0
Autumn	329.5	3.6	4.3	1990	2.9	1994	303.5
Annual	**1641.7**	**4.5**	**5.3**	**1989**	**4.0**	**1993**	**1493.7**

Notwithstanding its coastal location, Slapton is sunnier than Oxford throughout the year, with the exception of December and January. Oxford's long-term average annual total is 1494 hours, compared to 1641 hours at Slapton. On average, the summer months are sunnier at Slapton by about an hour per day. In exceptional months, sunshine exceeds 300 hours per month at both locations; in May 1989 there were 330.6 hours of bright sunshine at Slapton compared to 300.8 at Oxford.

Visibility is defined in the *Observer's Handbook* as the greatest distance at which an object can be seen and *recognised i.e.*, clearly identified (Meteorological Office, 1982).Visibility is recorded as being within a series of visibility ranges, and visibility objects are selected at the appropriate distances. At Slapton, the most distant object visible is the Start Point lighthouse, so 'excellent' visibility must be estimated from the general transparency of the atmosphere and the extreme clarity with which distant objects (in this case, radio mast wires on Start Point) can be seen. It can be appreciated, therefore, that visibility records, especially in very good conditions, are subjective, literally 'in the eye of the beholder'. Observations of mist and fog are more reliable, and have generally proved easy to interpret especially in urban areas in the aftermath of the Clean Air Acts (*e.g.*, Gomez & Smith, 1984). Long-distance visibility records have been much less straightforward to interpret (*e.g.* Gomez & Smith, 1987) and it is interesting that Lawrence (1976) makes almost no reference to this aspect in his review.

* There is a common rumour, probably apocryphal, that coastal resorts may 'massage' their sunshine figures in order to appear sunnier than their neighbours. It is reassuring to find that the summer sunshine figures for Slapton and those reported for nearby locations are very similar!

TABLE 11. Incidence of very poor and very good visibility at Slapton
(Average number of days per category per year, 1961-1997)

Visibility	**Fog**	**Moderate fog**	**Very poor visibility**	**Very good or excellent visibility**
Distance	<200m	<400m	<1,000m	>20km
code	< = 2	< = 3	< = 4	> = 8
January	0.2	0.6	3.4	5.9
February	0.2	0.9	3.4	3.6
March	0.5	1.2	3.7	5.2
April	0.4	1.0	2.7	5.4
May	0.3	0.6	2.5	5.8
June	0.2	0.6	2.7	6.6
July	0.2	0.6	2.5	7.2
August	0.2	0.6	2.7	7.4
September	0.3	0.8	3.0	5.8
October	0.1	0.4	2.5	5.7
November	0.1	0.5	2.1	8.0
December	0.4	0.8	3.2	5.8
Winter	0.9	2.3	10.2	15.4
Spring	1.2	2.8	8.8	16.4
Summer	0.5	1.8	7.9	21.2
Autumn	0.5	1.7	7.6	19.5
Annual	**3.1**	**8.5**	**34.4**	**72.4**

Table 11 gives the average number of days by month, season and year in which visibility at Slapton has been either very poor or very good. The incidence of poor visibility is greater in winter and spring, but coastal mist or haze can limit visibility to less than 1km at any time of the year. Fog is said to occur when visibility is less than 1,000 m (Code 3 or less) and thick fog when the visibility is less than 200 m (Code 1 or less). Fog occurs at Slapton on only 8.5 days each year, more than Plymouth's 5.6, but fewer than the Isles of Scilly (14) or Jersey (33). In such maritime settings, sea fogs dominate the statistics and radiation fogs are rare (Perry, 1997). Thick fog occurs on less than one day each year at Slapton. There is a tendency for more fogs in cooler, wetter years but these correlations are not statistically significant. In contrast to polluted urban sites, like Oxford, there is no evidence at Slapton of a significant reduction in fog days since the early 1960s (Gomez & Smith, 1984). If anything, there have been slightly more days with fog at Slapton recently, though the trend is a very weak one.

Days with very good or excellent visibility are more common in summer and autumn. Fig. 7 shows the total number of occasions each year in which very good (code 8) and excellent (code 9) visibility have been recorded. Given the caveats mentioned earlier, the significance of these results is not fully clear: either observers have become increasingly reluctant to recognise very clear conditions, or there has been a real decrease in the clarity of the atmosphere at Slapton. Statistical analysis indicates a consistent pattern of change in all seasons with the correlation between seasonal totals and the annual total ranging from $r = +0.79$ to $r = +0.87$. Table 12 confirms a consistent pattern of change in all seasons; winter

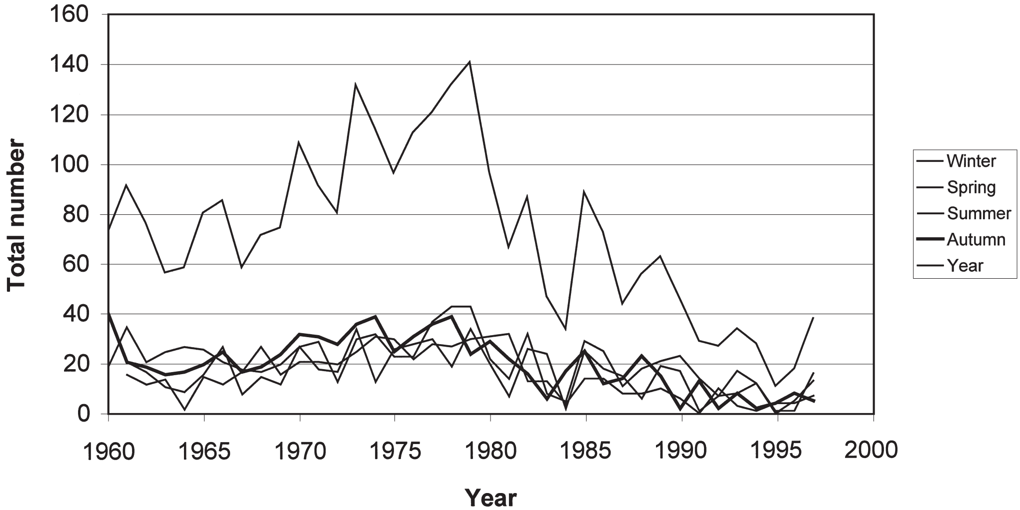

FIG. 7. The incidence of very good visibility at Slapton, 1961-1997.

has seen both the greatest improvement in the 1970s and the biggest deterioration since then. There are weak negative correlations between the North Atlantic Oscillation (NAO) index (Hulme & Barrow, 1997, appendix D3) and the excellent visibility totals, but the only significant correlation is between Autumn and NAO ($r = -0.34$, $p = 0.043$). This implies a tendency for better atmospheric clarity at Slapton when the westerly circulation is weaker (low NAO index) and there is more anticyclonic weather. Certainly there have been very few days of excellent visibility in winters since 1989, a period of consistently high NAO values with strong westerly circulation yielding mild, wet winters. This ties in with weak negative correlations between excellent visibility and both temperature and rainfall. However, there may well be other reasons for the pattern displayed in Fig. 7 and further research is needed to resolve the issue.

Although cloud types have been classified for nearly two hundred years, modern interest dates from the onset of aviation. Even so, there has been little systematic research into cloud cover until recently when the importance of clouds in 'greenhouse' warming has been recognised. Total cloud cover is the fraction of the celestial dome covered by all clouds visible, and is estimated at 09.00 hours GMT in oktas (or eighths) of the sky. Table 13 lists average totals of cloud cover at Slapton by month and season. Three categories are included: days where cloud cover is 2 oktas or less, days with cloud cover between 3 and 5

TABLE 12.
Average number of days of very good visibility per year over the last four decades at Slapton

	Winter	Spring	Summer	Autumn	Year
1960s	13	14	23	22	72
1970s	26	25	30	32	113
1980s	15	16	19	18	68
1990s	4	8	11	6	29

TABLE 13. Monthly and seasonal figures for cloud cover at Slapton (1961-1997 averages)

	Average 0-2	Average 3-5	Average 6-8
January	5	5	22
February	5	4	19
March	6	5	20
April	7	6	17
May	7	6	17
June	6	7	16
July	7	6	17
August	7	7	17
September	6	7	18
October	5	6	20
November	6	5	20
December	5	5	20
Winter	15	13	62
Spring	20	17	54
Summer	20	20	51
Autumn	17	17	57
Annual	**71**	**68**	**224**

oktas, and days where cover is 6 oktas or more. About 61% of days have high cloud cover at Slapton with equal fractions in the two lesser categories. As might be expected from the rainfall figures, there is a tendency for more cloud cover in autumn and winter. There has been a tendency for the number of cloudy days (6-8 oktas) to decrease during the study period, although the correlation is not significant ($r = -0.31$, $p = 0.068$); a concomitant increase in cloud-free days (0-2 oktas) shows an even weaker correlation ($r = +0.14$). There is a weak negative correlation between NAO index and high cloud cover ($r = -0.23$); it might be expected that stronger westerly circulation would mean more cloud cover but this is apparently not the case. The correlation between annual rainfall and days with high cloud cover is virtually zero.

It is clear that more work is needed to disentangle the complex relationships between circulation patterns and weather types. Most attention has hitherto been paid to temperature and rainfall: the way in which other weather variables like visibility and cloud cover respond to changes in circulation has, by comparison, received scant attention.

EVAPORATION AND THE WATER BALANCE

Insufficient variables are measured at the Slapton weather station to allow daily estimates of evaporation to be calculated using the Penman formula. The American climatologist, Thornthwaite developed a method of calculating potential evaporation using monthly temperature data. Burt & Shahgedanova (1998) used the Thornthwaite method to calculate an historical record of evaporation losses for the Radcliffe Meteorological Station, Oxford using long-term (since 1815) monthly observations of mean air temperature and rainfall. Following exactly the same method, monthly values of potential evaporation (PE), actual evaporation (AE) and soil moisture deficit (SMD) have been calculated for the Slapton climate record. Full details of the Thornthwaite method are given in Dunne & Leopold

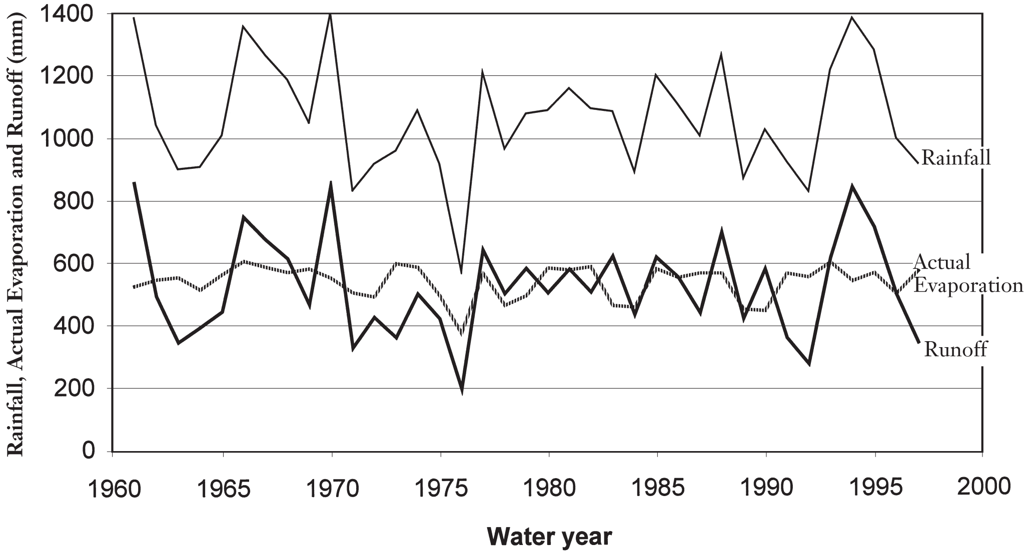

FIG. 8. The water balance for the Slapton Wood catchment.

(1978) and the Penman method of calculating SMD and AE is given in Shaw (1994).

Given rainfall (R) and AE, runoff for water years can be calculated simply as:

Runoff = R - AE

The water year is, by convention, taken to begin on 1 October, at which time water storage in the catchment is assumed to be at a minimum; the year number is given for the calendar year in which the majority of the water year lies. Fig. 8 and Table 14 show water balance data for the study period. As expected, AE is relatively conservative, usually between 500 and 600 mm, and falling significantly below 500 mm only in years with very warm summers: 1976, 1983, 1984, 1989 and 1990. On the whole, therefore, annual rainfall is the main determinant of annual runoff. Normally, just under half the rainfall leaves the catchment as stream discharge; in the wettest year (1970) this figure rose above 60% but fell well below 40% in the driest year (1976).

Although there is a complete hydrological record for the Slapton Wood catchment, the raw data are in the form of charts which must be transcribed before discharge can be calculated. Only limited sections of the record have so far been analysed. Fig. 9 shows monthly data for the water years 1975-78, which includes the extreme drought of 1975-76 (Burt *et al.*, 1988). The normal pattern of high winter runoff is clear in three years, but there was little runoff during the winter of 1975-76 which was unusually dry (see above). It

TABLE 14. Water balance data for water years 1961-1997. In addition to average figures, data for the wettest and driest years are included. 'Runoff percent' is the percentage of rainfall returned as stream runoff

Year	Rainfall	Actual Evaporation	Runoff	Runoff percent
mean	1067	540	527	48
1970	1403	554	849	61
1976	575	377	198	34

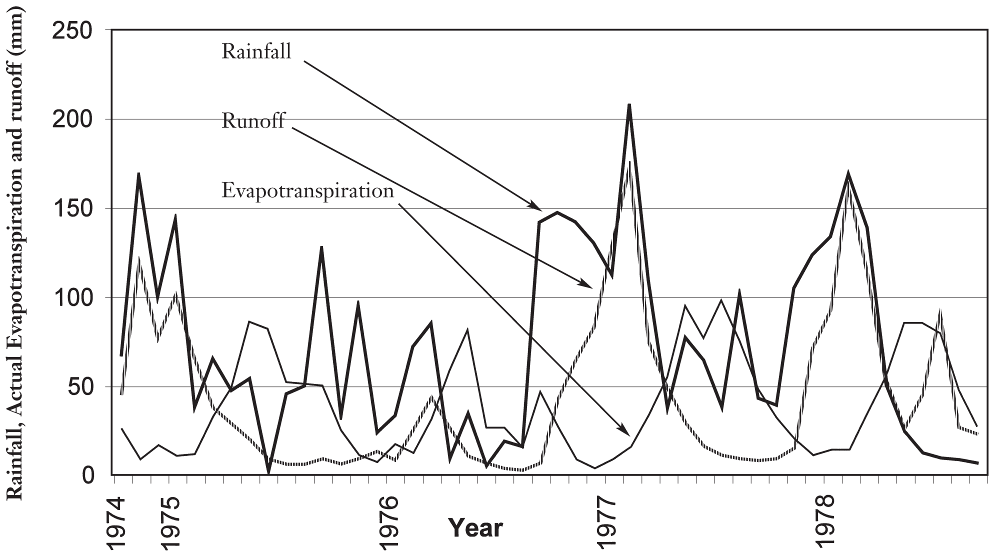

Fig. 9. The water budget for Slapton Wood catchment, 1974 - 1978.

is notable too that the normal annual cycle of evaporation was interrupted in 1976 when AE fell to very low levels, well below PE because of the very dry soils.

For a short period, the Institute of Hydrology (IoH) operated a Didcot™ automatic weather station in the Slapton Wood catchment, approximately one kilometre from the field centre. Blackie (pers. comm.) provided the following water balance for the Slapton Wood catchment for the 1990 water year (beginning 1-10-89); figures derived using the Thornthwaite method as described above may be compared:

	IoH results	Thornthwaite method
Precipitation	1015 mm	1026 mm
Potential evaporation	767 mm	679 mm
Actual evaporation	475 mm	446 mm
Stream runoff	540 mm	580 mm

Although the Thornthwaite method underestimates PE, the calculations of AE and runoff are acceptably close; so too are the two measurements of annual rainfall.

Perspective

The climate at Slapton is very favourable by British standards: mild and wet with few frosts and minimal snowfall. A good deal of the nature reserve's ecological richness must relate to its south-west location, on the very edge of the Atlantic Ocean, well buffered from continental and polar influences.

Resort weather

Perry (1968) identified a maximum of 25°C as the threshold for a 'summer day'. On this basis Slapton fares rather poorly, with only two such days on average each year. Nevertheless, for holiday makers and local residents alike, the climate at Slapton remains attractive throughout the year, warm and sunny in the summer, and mild at other times. The sunshine record is too short to allow effective application of the various summer weather indices that have been devised. Davis (1968) proposed a summer weather index (I):

$$I = 10T + 20S - 7R$$

where T is the mean daily maximum temperature (°F) for the three summer months, June, July and August, S is the daily mean sunshine in hours for those three months and R is the total summer rainfall in inches. For the eleven years of record 1987 to 1997 inclusive, the Davis index averages 765 at Slapton which compares well with the much longer period averages (generally 1893-1967) provided by Davis for other places on the south coast like Plymouth (744) and Southampton (787). On the east coast, Felixstowe (775) has a similar index value, but Slapton is well above Scarborough (716) and Durham (710). The Davis index has always exceeded 700 at Slapton and in two years was over 800: 1995 (821) and 1989 (865); the range at Plymouth is 615 (1912) to 861 (1949).

Climate change

It is no surprise that the climate of Slapton Ley is strongly influenced by the general circulation of the atmosphere in the North Atlantic region. Changes in circulation over the North Atlantic Ocean are associated with shifts in storm tracks and the varied pattern of air mass movement experienced over the British Isles. Since two centres of action - the Azores High and the Icelandic Low - dominate the pattern of surface pressure over the Ocean, a useful index to describe conditions upwind of the British Isles is the difference in pressure between the Azores and Iceland (Davies *et al.*, 1997). The North Atlantic Oscillation index (NAO) provides an indication of the strength of the westerly circulation in the north Atlantic. When the NAO index is high - a strong westerly or 'zonal' circulation - storm tracks push further into northern Europe, with higher temperatures and higher rainfall in northern Britain, though not necessarily in the south. When the NAO index is low - a more 'meridional' circulation - there is a greater tendency for easterly air flow and blocking anticyclones over Scandinavia become more influential (Davies *et al.*, 1997). Hulme & Barrow (1997, appendix D.3) list values of the NAO index from 1865. These values are used here to interpret the recent climatic record at Slapton.

Table 15 lists correlations between annual average values of the NAO index and various annual figures from the Slapton climate record. Only the correlation between NAO index and annual temperature is significant, but this is a strong correlation, almost at the 99% confidence limit. This suggests that strong westerly circulation over the Atlantic brings warmer weather, especially in winter when the impact of polar continental easterlies is minimised. Both NAO and temperature have increased significantly over the last four decades, as Fig. 10 shows. There is a tendency for worse visibility, less cloud cover, and lower wind speeds with high NAO values, but the correlations are not significant. This all suggests that storm tracks tend to be pushed well to the north of the south-west peninsula when the circulation is strongly zonal. Warmer, calmer weather with lower cloud cover suggests increased influence from the Azores High. Fewer days with excellent visibility may reflect the high concentration of sea salts in maritime air masses.

There is no correlation at Slapton between annual values of the NAO index and annual precipitation ($r = 0.048$). However, when 5-year running means are employed, the correlation between improves significantly ($r = -0.401$). Thus, in general, a stronger westerly flow means lower annual rainfall at Slapton, as Fig. 10 indicates. A simple explanation would invoke northern movement of storm tracks, with the south west

TABLE 15. Pearson's correlation coefficients between selected annual data for Slapton, 1961-1995. Correlations significant at p=0.05 are *italicised*; correlations significant at p=0.01 are in **bold type**. Climatic variables are as follows: AnnualT = annual average temperature; AnnualR = annual rainfall total; GoodVis = number of days each year with very good or excellent visibility; cloud6-8 = number of days each year with high cloud cover; cloud0-2 = number of days each year with low cloud cover; Wind = annual average wind speed

	Year	NAO	AnnualT	AnnualR	GoodVis	cloud6-8	cloud0-2	Wind
Year	1 .000							
NAO	*0.406*	1.000						
AnnualT	*0.402*	*0.415*	1.000					
AnnualR	0.128	0.048	-0.168	1.000				
GoodVis	**-0.497**	-0.225	-0.187	-0.211	1.000			
cloud6-8	-0.312	-0.227	-0.383	0.005	0.117	1.000		
cloud0-2	0.138	0.033	0.318	-0.075	-0.236	**-0.634**	1.000	
Wind	**-0.488**	-0.19-0	-0.226	-0.022	**0.547**	0.203	*-0.411*	1.000

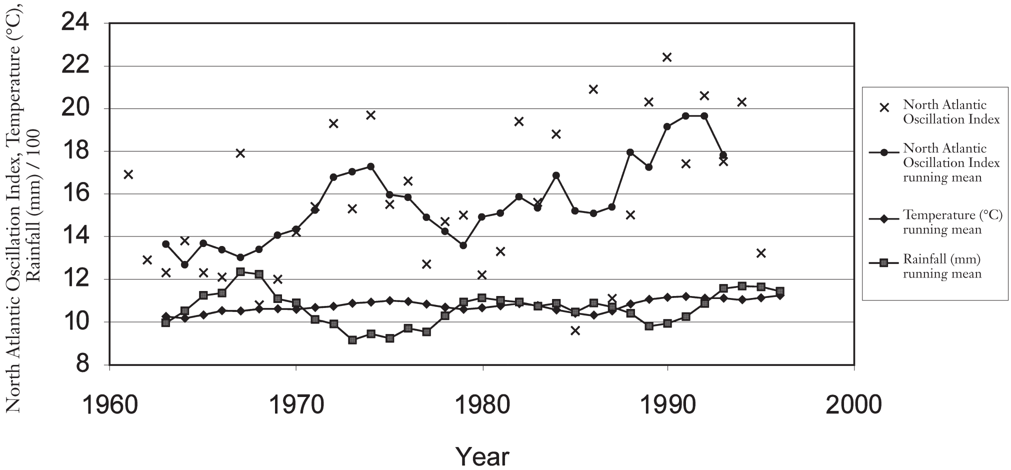

FIG. 10. North Atlantic Oscillation Index (NAO), 1961 - 1995, together with 5-year running means for NAO, temperature and rainfall.

peninsula coming more under the influence of the Azores High. However, since the late 1980s when the NAO has been very strong, rainfall has increased at Slapton too, especially in winter. At times of very high NAO it seems that the western side of Britain becomes generally wetter: in Scotland, rainfall has increased dramatically on the west coast in recent years and yet, further east, no such increase has been observed (Werritty, pers. comm.). This may indicate a stronger southwest/northeast circulation perhaps, rather than a simple increase in truly zonal flow.

Linacre (1992) recommends the use of graphs of cumulative deviation of individual values from the overall mean as a means of identifying discontinuities within a climatic record. Fig. 11 shows cumulative deviations for annual values of NAO, temperature and rainfall at Slapton. The close association of NAO and temperature is clearly evident, confirming the enhanced influence of Atlantic air masses on the climate at Slapton over the last three decades, once the 1960s cooling was over. Rainfall again shows a more variable

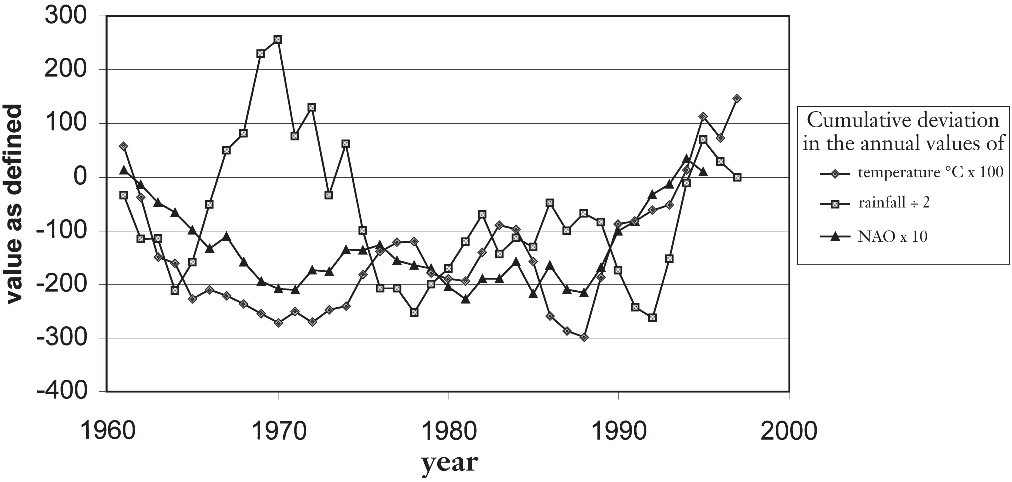

FIG. 11. Cumulative deviations for the annual values of the North Atlantic Oscillation Index (NAO) and those of mean temperature and rainfall at Slapton.

pattern, less clearly related to NAO. Nevertheless, NAO, temperature and rainfall have all increased significantly in the 1990s, and it remains to be seen whether this trend continues in line with global warming. If it does, the climate at Slapton Ley may become more strongly seasonal, with summer drought and winter downpours superimposed on record temperatures. One can only speculate on what such a climate will mean for the ecology of the Slapton Ley National Nature Reserve.

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