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Stormy Years

On the Association between the El Niño/Southern Oscillation phenomenon and the occurrence of typhoons in the Marshall Islands

Report to the Federal Emergency Management Agency
Region IX, San Francisco

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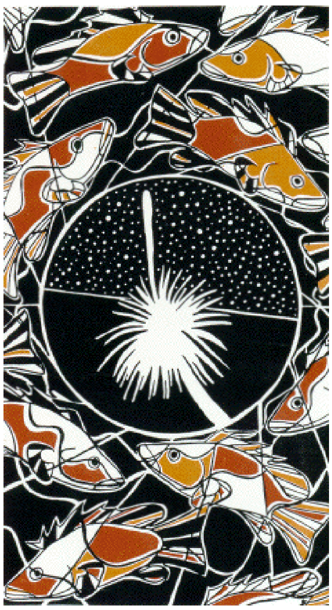

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NOTE

Due to differences in the fonts used, the lay-out of this pdf version of the report varies slightly from the 1994 original.

Abstract

An analysis of the historic record of typhoons in the Marshall Islands has identified a significant association between the occurrence of the El Niño/Southern oscillation phenomenon (ENSO) and the occurrence of typhoons in the Marshall Islands. Whilst typhoons normally occur further to the east, the warming of the ocean waters around the Marshall Islands, as part of the ENSO phenomenon, generates typhoons further to the west.

The results suggest that typhoons are 2.6 times more likely to occur during ENSO years, with a 71% chance of a typhoon striking during an ENSO year, and only a 26% chance of one happening during a non-ENSO year.

This has implications for planning and public safety, which the relevant authorities may wish to take note of.

Introduction

This study compiles data on typhoons known to have affected islands and atolls of the Republic of the Marshall Islands. Drawing on data drawn from the historic literature and from modern weather records, a case will be made showing that there is an association between the El Niño/Southern Oscillation phenomenon and the occurrence of typhoons.

Background

The Marshall Islands (*Aelon Kein Ad),* comprising 29 atolls and 5 islands, are located in the north-west equatorial Pacific, about 3790km west of Honolulu, about 2700km north of Fiji and 1500km east of Pohnpei. With the exception of the two northwestern atolls, Enewetak and Ujelang, the Marshall Islands are arranged in two island chains running roughly NNW to SSE: the western Ralik Chain and the eastern Ratak Chain (figure 1). Majuro Atoll, with its close neighbour, Arno Atoll, is located on the northern margin of the southern group of atolls of the Ratak Chain (or *Ratak-rak*). Not counting the five islands, Jemo, Jabwat, Kili, Lib and Mejit, the atolls of the Marshall Islands range from very small, with less than 3.5km^2, such as Nadikdik (Knox) Atoll to very large. With 2,173km^2 lagoonal area, Kwajalein Atoll has the distinction of being the atoll with the world's largest lagoon.

Given their generally low-lying character, the atolls of the Marshall Islands are very prone to the effects of typhoon damage. Human populations, past and present, are affected as are the atolls' vegetation, wildlife and reef ecology. Depending on the strength of the storm whole islands can be depopulated and, in the extreme, even washed away in their entirety. Historic references speak of human tragedy of vast proportions.

Today, much has been altered on the atolls of the Marshall Islands and little in terms of traditional way of life and patterns of settlement remains. However, while modern building standards can mitigate the wind damage caused by a typhoon, the erosive force of the storm surge is less easily mitigated. Detailed case studies of historic typhoons document the effects of typhoons, and allow the evaluation of the vulnerability of various settlement locations.

This report was developed as an offshoot of work conducted by one of the authors (DHRS) on the history of typhoons in the Marshall islands in order to generate data which would allow generalisations of the frequency of impact of typhoons affecting Marshallese populations in pre-European times.

The data

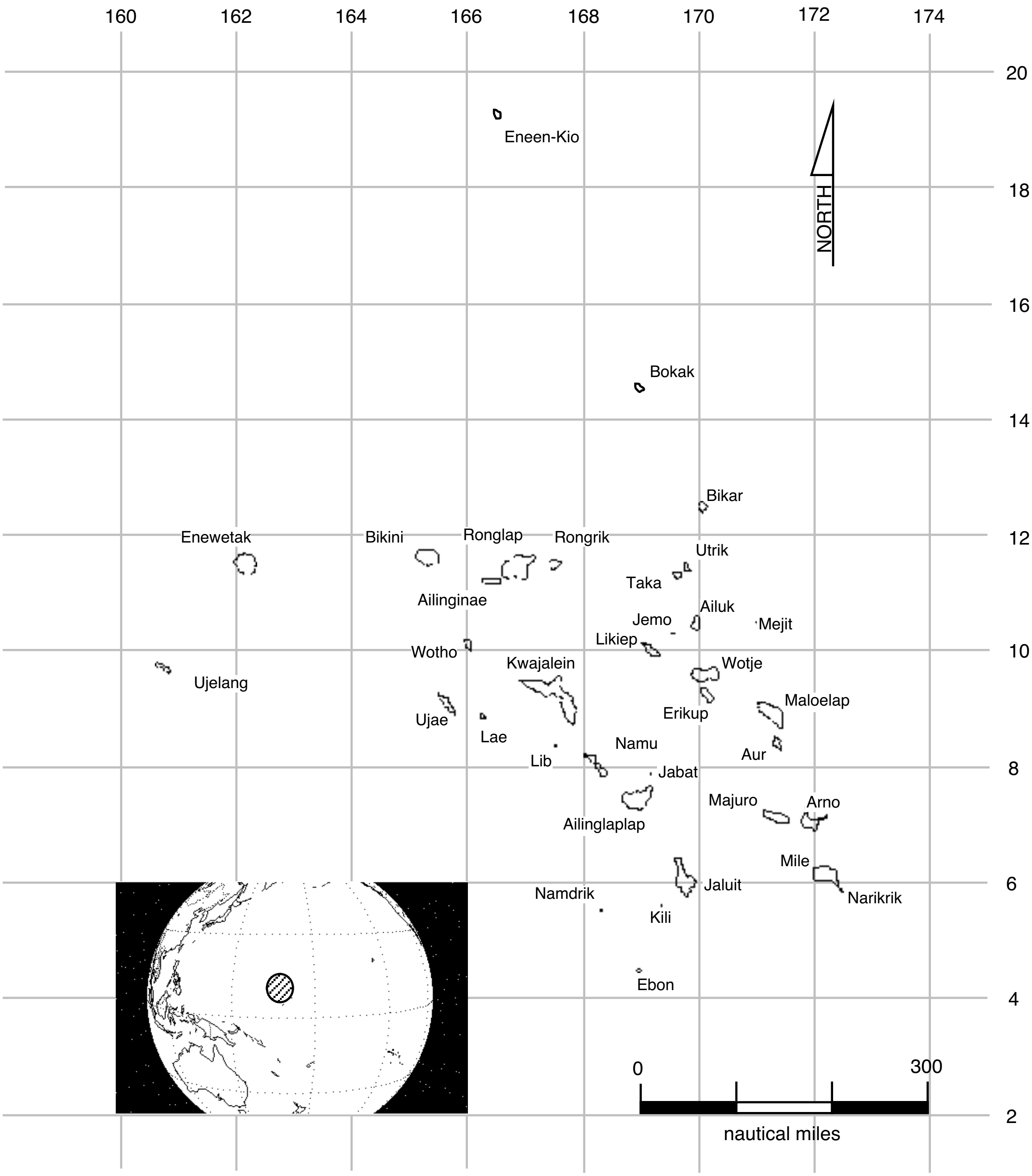
The data sets available for the analysis comprise the following sources:

- German archival records;
- references in published travelogues and accounts on the Marshall Islands
- references in unpublished diaries of 19th century traders
- references in Japanese mandate reports;
- references in US military publications on the Marshall Islands; and
- weather and typhoon track data supplied by Joint Typhoon Warning Center in Guam.

Some of these sources warrant further discussion.

German Archival records

Screened were the files of the German Admiralty, both naval and civilian correspondence (Kriegs– and Friedensakten, held by the British Navy Archives), correspondence files of the German Colonial Office, Berlin (Reichskolonialamt; German Archives Potsdam) relating to the administration of the Marshall Islands, the health situation and commerce, correspondence files of the German Governor–general for the Pacific, resident in Rabaul (National Archives of Papua New Guinea); and contemporary newspaper articles in the *Deutsche Kolonialzeitung* and the *Deutsches Kolonialblatt*.



.c8.Figure 1 Map of the Marshall Islands

Table 1. The atolls of the Marshall Islands.

	Location (Lat. & Long.)		No. of	Land area (km^2)		Lagoon area (km^2)		Ratio land to lagoon area	
Atoll	North	East	Islets	area	rank	area	rank	ratio	rank
Ailinginae	11°10'	166°20'	25	2.80	20	105.96	19	2.64	12
Ailinglaplap	7°26'	169°00'	52	14.69	3	750.29	6	1.96	17
Ailuk	10°20'	169°52'	35	5.36	17	177.34	17	3.02	11
Arno	7°10	171°40'	83	12.95	4	338.69	12	3.82	9
Aur	8°12'	171°06'	42	5.62	16	239.78	14	2.34	15
Bikar	12°15	170°6	6	0.49	31	37.40	26	1.32	20
Bikini	11°30'	165°25'	36	6.01	13	594.14	9	1.01	24
Bokak (Taongi)	14°32'	169°00'	11	3.24	19	78.04	23	4.15	8
Ebon	4°38'	168°40'	22	5.75	15	103.83	20	5.54	5
Eneen-Kio (Wake)	19°18′	166°35′	3	7.38	11	12.90	28	57.20	1
Enewetak	11°30'	162°20'	40	5.85	14	1,004.89	3	0.58	30
Erikup	9°08'	170°00'	14	1.53	26	230.30	15	0.66	28
Jabwat	7°44'	168°59'	1	0.57	30	—	34	100.00	34
Jaluit	6°00'	169°34'	84	11.34	5	689.74	7	1.64	18
Jamo	10°7'	169°33'	1	0.16	32	—	35	100.00	35
Kili	5°37'	169°7'	1	0.93	29	—	33	100.00	33
Kwajalein	9°00'	166°05'	93	16.39	1	2,173.78	1	0.75	27
Lae	8°56'	166°30'	17	1.45	27	17.66	27	8.21	4
Lib	8°21'	167°40'	1	0.93	28	—	32	100.00	32
Likiep	9°54'	169°10'	64	10.26	6	424.01	10	2.42	14
Majuro	7°3'	171°30'	64	9.17	8	295.05	13	3.11	10
Maloelap	8°40'	171°00'	71	9.82	7	972.72	4	1.01	23
Mejit	10°17'	170°52'	1	1.86	23	—	31	100.00	31
Milli	6°05'	171°55'	84	14.94	2	759.85	5	1.97	16
Nadikdik	6°20'	172°10'	18	0.98	28	3.42	30	28.79	3
Namo	7°55'	168°30'	51	6.27	12	397.64	11	1.58	19
Namorik	5°37'	168°7'	2	2.77	21	8.42	29	32.92	2
Rongelap	11°19'	166°50'	61	7.95	10	1,004.32	2	0.79	26
Rongerik	11°20'	167°27'	17	1.68	25	143.95	18	1.17	22
Taka	11°18'	169°35'	5	0.57	29	93.14	22	0.61	29
Ujae	9°00'	165°45'	14	1.86	22	185.94	16	1.00	25
Ujelang	9°50'	160°55'	32	1.74	24	65.97	24	2.63	13
Utirik	11°12'	169°47'	6	2.43	22	57.73	25	4.22	7
Wotho	10°05'	165°50'	13	4.33	18	94.92	21	4.56	6
Wotje	9°26'	170°00'	72	8.18	9	624.34	8	1.31	21

The German Admiralty and Colonial office files are held by the Bundesarchiv in Potsdam (Berlin), and as microform copies by the Australian National Library, Canberra (obtained from the then Zentral-Archiv der Deutschen Demokratischen Republik). The Australian Archives, ACT Records Depository, Canberra, hold microfilm copies of the files of the German Governor for the South Seas, Rabaul, the originals of which are owned by the Government of Papua New Guinea and held by the Public Record Services of PNG, Port Moresby.

Material not accessible for the present study, but potentially of great interest are the archives of the Sacred Heart Mission in Hiltrup, Germany, which are likely to contain reports and accounts of the Catholic missionaries, and the logbook of SS Germania, which rode out the storm in Jaluit lagoon.

The German Government files on the period are of mixed quality. Each year the colonial administrator had to file an annual report, many of which are contained in the files of the Foreign Office, Colonial Office. However, the reports are of mixed quality, depending on the administrators zeal. Dr. Georg Irmer, or example, filed very detailed reports (Irmer 1894; 1895; 1896; 1897) which contain detailed information on shipping, copra-production, and general information for the financial years 1894/95 to 1896/97. Dr. Senfft, interim administrator for the financial year 1897/98 followed Irmer's lead (Senfft 1898). The new administrator, Brandeis, however, filed a shorter report in his first year (Brandeis 1899), and filed brief and not at all informative reports from then onwards (cf. Brandeis 1900; 1901, 1906). Brandeis had been in administration before and was not a newcomer to the office. There appears to have been no complaint from the German Colonial Office as to the brevity of the reports. From 1906 onwards, the Marshall islands ceased to exist as an independent protectorate and became a sub-district of the Marianas and Caroline Islands Colony, Records of that period are very sparse.

Published accounts on the Marshall Islands

Researching the early history of typhoons was even more complex. The main sources for the early life and economic situation of the Marshall Islands make no mention of typhoons (e.g.. Warren 1860; Kubary 1873; Anonymous 1886; Finsch 1886; Hager 1886; Hernsheim 1880; 1887; Grundemann 1889).

We have occasional access to data contained in diaries, such as that of John Lyell Young, who stayed on Ebon Atoll in 1877.

The reliability and completeness of the data

Typhoon records are not that well developed, as constant documentation in a central data centre did not exist prior to 1945. We need to understand that typhoons needed (i) to be observed by people and (ii) if it they were, information about them needed to be passed on to whom who noted it down. During the period of autonomous government in the Marshall Islands, i.e. before 1885, this information would have been only collected by traders, Thus, if we look at the distribution of traders in the pre-German period we note that the information on typhoons for some atolls (set out in table 3) and the presence of traders are reasonably correlated. After 1885 recording of typhoons increased, but was centered on Jaluit as the center of the German Colonial administration.

The data sets mentioned above are of varied states of completeness and accuracy. For convenience, the data sets can be grouped into four periods, which coincide with major historic periods in the Marshall Islands:

1. the period before the beginning of the German Colonial presence (pre-1885)
2. the period of the German Colonial Administration (1885—1914)
3. The period of the Japanese Mandate over Micronesia (1914—1945); and
4. the period of the US administration

Period before the beginning of the German Colonial presence (pre-1885)

The data for this period are derived from published travelogues, accounts of sea captains and passengers published in contemporary newspapers, missionary publications (re. voyages of the *Morning Star*), unpublished diaries and the like. The canvassing of the sources is likely to be incomplete, even though a rather exhaustive search of the literature has been completed (see bibliography for sources consulted). In addition, the sources themselves are not likely to have recorded every typhoon occurring in the area, because they were either not present at the time, or the typhoon struck in a different part of the Marshalls. The data "net" is governed by the presence of recording stations", in this case the stations of European traders likely to witness or hear of typhoon events (see Freidrichsen 1875, Spennemann 1992 for the distribution of trading stations in 1875).

Period of the German Colonial Administration (1885—1914)

The records for that period are of mixed quality. While the records for the first ten years of the colony are likely to be as complete as the German colonial officers knew, we have to consider that, like in the period before, some typhoons and typhoon-related floodings may well have escaped the notice of the administrators. For the period 1906 to 1914 the data are not as reliable as one could wish for. A perusal of the German files dealing with meteorological and climatological observations provides rainfall and some temperature data, but shows that typhoons were not systematically recorded (Jaluit Harbourmaster 1894-1912, Steinbach 1893a; 1893b; 1894; 1895a; 1895b).

The typhoon record shown in table 2, conflicts with statements by Jeschke (1905) that "as far back as the memories of the natives go, the Marshall Islands have never been visited upon by typhoon." Storm surges, he says, have been reported, but cyclonic wind systems have not. This statement reflects the Jaluit centered knowledge base of the European traders at the turn of the century. Schwabe (1905a) asserts that among traders and locals alike, there had been a notion that typhoons would not occur as far east and as far south as Jaluit, leading to a false sense of security.

Period of the Japanese Mandate over Micronesia (1914—1945)

The data for typhoons during the period of the Japanese mandate of the South Seas are very limited, due to the overall inaccessibility of the literature. While there are some references to Japanese-language publications, these could not be followed up for the purposes of this study, and the authors had to rely on secondary references in US military intelligence and similar literature.

Period of the US administration

The data since 1945 have been obtained from the Joint Typhoon Warning Center in Guam and can be considered to be complete for the purposes of this study.

History of typhoons in the Marshall Is.

Typhoons only intermittently occur in the Marshall Islands since the main centers are further south and further to the west, namely Guam and Palau (Freeman 1951). Table 2 lists the typhoons known to have occurred in the Marshall Islands. The data available for analysis are very restricted. Perusal of table 3 shows that there are serious data gaps in the recording of typhoons, with some atolls not represented at all (such as Enewetak). The following discussion provides descriptions on some typhoons.

Typhoon histories

The first typhoon recorded for the Marshall Islands happened in the 1840s. It devastated Likiep Atoll and cost the lives of the greatest part of the population (Goetze 1914). Erdland (1906:272) mentions having met an eye-witness in 1904 or 1905 (?), who still remembered the 1840s flooding.

A typhoon in about 1850 affected the northern Marshalls and decimated or completely wiped out the population of Rongelap and Rongerik Atolls (Krämer & Nevermann 1938:51;81).

Erdland (1914:18) mentions that his informant Benjamin (†1904) had as a child heard about a typhoon which destroyed much of Ebon and devastated all coconut and breadfruit trees there, leading to widespread starvation and killing of people.

In addition, we have data for Ebon, which show that in 1857 a major food shortage occurred and about 800 people of a total of 1300 left Ebon for Jaluit Atoll (Krämer & Nevermann 1938:30; Hezel 1983). The cause of this food shortage of such magnitude is not explained in the records, but a typhoon-related cause is extremely likely.

In 1854 a typhoon struck Likiep Atoll and Mejit Island (Erdland 1906:185; Krämer & Nevermann 1938:83). Given its location between the two places, it is extremely likely that Ailuk Atoll was also affected, albeit this is not recorded in the literature.

In February 1864 the missionary packet *Morning Star*, Captain Samuel James, put in at Ujelang. The island was found deserted after a "volcanic convulsion had laid waste of the island" (Hezel 1979:125, Ward 1967: VI 349). In the absence of known submarine volcanic vents,[1] it is most likely that this observation represents damage wrought by a typhoon, rather than a volcanic explosion. The same event is reported in *The Friend*, a Honolulu-based church newspaper of 1 May 1864. According to Captain James the event

> "occurred only a short time previous to his visit, and all the tree and leaves were scorched with the hot gases, but at present there are no appearances of active fires. The land embracing a space of three or four hundred feet square was torn and thrown in every direction, resembling the braking up of ice on a river in the spring" (cited after Ward 1967: VI 349).

The scorching of vegetation as a result of salt spray caused by cyclonic storm surges is a well known phenomenon and caused the leaves to either wilt and brown (Fosberg 1957; Spennemann, pers. obs.) or even to turn black (see description of Jaluit in 1875, below).

In 1864 a different typhoon struck Ebon Atoll and devastated the island. The resident missionary, Snow noted:

> "You would hardly know the end of the island. Every green bush and shrub is gone. The water tore everything before it" (Snow 1864).

Houses, coconut palms and breadfruit trees had been washed off the island. In addition, canoes and a boat had been destroyed (Snow 1864).

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1 A claim was made in the *National Gazette and Literary Register* (Philadelphia) on May 6, 1864, that the atoll of Aur contained an active volcano (see Ward 1967: I 168). This message is most likely copied from the same source *The Friend* drew upon. While there are several submarine vents of Miocene age in the Marshalls, there are no active

The most devastating effects of typhoons are known from Ujelang. Gulick (1862) estimated the population in 1860 to be about 1000 people. The German South Seas Handbook for 1913, possibly drawing on the same source, states that the population of that atoll was about 1000 heads in the 1850s (Südsee-Handbuch 1913). A severe cyclone hit the island in 1870, and all but 20 people perished. Most of these 20 people moved at least temporarily to Jaluit, so that in 1878 the total population had shrunk to 6 (Witt 1881).

In 1874 Ailinglaplap was badly hit by a cyclone coming from the southwest (Witt 1881:528) and had not yet recovered by 1880. The population given by Witt (1881:529) counted 220 heads in 1880, from an estimated high of 500 or 600 in the early 1870s.

In early November 1875 a typhoon struck Jaluit Atoll, where three ships were driven ashore, all belonging to the German trader Adolph Capelle (Colcord 1875; Young 1877; Hezel 1979:132). In 1875 the atoll of Jaluit was struck by a severe typhoon. A. Colcord, wife of the master of the missionary packet *Morning Star* reports in her diary:

> "At the time they were having a tornado here, which drove ashore three schooners belonging to Capelle & Co., and a Russian barkentine named Julie Reitz—ship and cargo of copra a total loss. [Jaluit is] quite a desolate sight; ships bilged on the beach, trees uprooted in every direction, and blocking the roads and paths. Hardly a green leaf to be seen; even the leaves of the bushes shrivelled and blackenend. Some of the trees bent halfway to the ground by the wind still remain, so one can almost imagine the tornado still going on! The people are very downcast; so many breadfruit and coconut trees uprooted, and most of those standing [with] leaves all dead. They fear a famine" (Colcord 1875:42).

Continuing the voyage from Kosrae to Honolulu,

> "we passed Hunters Island [=Kili] before dark. The trader's house was unroofed, trees blown down, and the island looks shipwrecked. … Arrived at Namorik about 8am. Trees look better here, though teacher Matthew, who came off, says their breadfruit tress are blown down and they felt the tornado." Colcord 1875:43).

Colcord further mentions that Ebon was affected, but that little damage had occurred (Colcord 1875:44). Young, living on Ebon in 1876 and 1877 makes comments on the 1875 typhoon, but does not mention any damage for Ebon. Majuro is also reported as unaffected (Colcord 1875:45), which appears understandable given the low latitude at which the typhoon struck. Mile Atoll could have been affected, but as the vessel did not sail past it, no data could be obtained about it.

Young reports a typhoon which struck the northern islands.

> Natives are in much fear of a destructive gale (Lañ) like the one which desolated the northern islands in November 1875 (Young 1877:152; entry for July 14th 1877)

> "At 3:30 am a very heavy squall came suddenly from W. which lasted for half an hour; the heaviest squall I have seen in the islands; it blew with perfect hurricane force and was reinforced with thunder and lightening. The natives think this is the beginning of a hurricane. Not a pleasant prospect when one considers that a rise of a hurricane wave of 8 feet would sweep this islet bare as it did Kwajelen Island in 1875, drowning the inhabitants." (Young 1877:153; entry for July 17, 1877)

In 1876 a vessel visited Kili Islands and found it deserted on account of the same typhoon (Young 1877; Hezel 1979:133). Witt (1881:533) mentions that Kili was devastated by a cyclone in 1874. The island is reported as uninhabited in 1876 because of that (Hezel 1979:133). The 1874 cyclone had its strongest winds from the SW (Witt 1881:535). It is most likely, given the accuracy of Colcord's observations, that Witt had mixed up the years for the Kili typhoon, albeit it is possible that we are dealing with two separate events (see also above for Ailinglaplap typhoon of 1874).

In 1890 a typhoon struck Uterik, and most likely also neighbouring (uninhabited) Taka (Fosberg 1956:72).

In January 1899 flooding of several atolls occurred, most likely as the result of a typhoon. On Arno a piece of land with some 100 coconut palms on it was washed away. On Likiep three islets (Lato, Tinegar and Kapenor) were affected, with between 100 and 130m of land washed away (Brandeis 1899; see also pictorial data in deBrum Archives, Alele Museum).

In 1900 a typhoon struck the southern Marshalls:

> "We had a true Marshall Storm from Ebon to Mille [sic]. The schooner Jaluij capsized and sank in the lagoon and the *Hercules* lost a boat from the davits lying under Namerik [sic], while we made 200 miles windward in four days." (Walkup 1901).

The major typhoon of 1905 will be described in greater detail further below. It should be pointed out, however, that Jaluit Atoll had experienced a low frequency of storms and no typhoons since the 1860s and a belief had set in among the European settlers community on that atoll that Jaluit was not prone to typhoons at all (see Krämer & Nevermann 1938).

The German administrator Merz (1911b) had received reports that a typhoon had hit the northern atolls of Enewetak and Ujelang in late that year, and requested the visiting German cruiser *Condor* to investigate. Merz asked the *Condor* to ship 50 bags of rice as hand outs in case of need. The *Condor* duly visited Enewetak and was informed by the local trader that no storm let alone typhoon had been encountered

(Ebert 1912). On Ujelang, however, tropical storms and typhoons had taken place on 16/17 October and 2/3 November 1911. On the latter occasion, on 2/3 November, some 800 palms had been blown over, most breadfruit trees stripped and or felled and all coconut palms stripped of all flowers, seriously setting back the copra production (Ebert 1912). In January 1912 another typhoon visited Jaluit, which was not as devastating as that of 1905. Notwithstanding, the newly built hospital was destroyed, several houses lost their roofs and a new copra plantation on Jabwor had been destroyed by inundation and deposition of corals (Mommsen 1912).

After the establishment of the U.S. administration in Micronesia, following Japan's defeat in the Pacific War, data on typhoons become more frequent. Utirik Atoll was severely hit by typhoon *Georgia* which struck the atoll on 21 March 1951 coming from south-southwest (Fosberg 1955a:4; Fosberg 1956).

The typhoon surge destroyed a narrow part of the island and washed away inter-tidal sand accumulations. Typhoon *Ophelia* hit Jaluit Atoll in 1958. The effects of this typhoon are very well documented in the literature (Blumenstock 1958; 1961; Blumenstock *et al.* 1961; McKee 1959).

Climatic extremes, such as typhoons are well known on the far northern atolls. In living memory, *i.e.* since 1935 (first permanent settlement there) the atoll of Eneen-Kio (Wake) was hit several times, in 1940, 1941, 1952 (by Typhoon *Olive*) and in 1967 (Dierdorff 1943; Lee 1980; Spennemann 1991). During the 1940 typhoon a PanAm flying boat, a marine railway and the entire floating pier were destroyed, while the damage to the shore installations of PanAm was also substantial (Dierdorff 1943). A great amount of flotsam was encountered scattered on the surface of Wake when the first construction team for the PanAm station arrived (Spennemann 1991). This shows that such events had also occurred in the past.

The uninhabited Bokak Atoll (Taongi) shows geomorphological indication of having been repeatedly water washed by typhoon surges (Thomas 1989), but no dates can be advanced. In 1979 Tropical Storm *Alice* approached the Marshall Islands as close as 40nm east of Kwajalein Atoll. While Majuro did not experience any wind effects, the storm surge flooded the D-U-D area. In 1988 Typhoon *Roy* passed, among other atolls, over the island of Lib, where about 50% of all housing was destroyed (pers. comm. C.Curtis) In November 1991 tropical storm *Zelda* hit the central Marshalls and developed into a typhoon between the Marshalls and Pohnpei. In January 1992 typhoon *Axel* struck the southern Marshalls inundating parts of Jaluit, Mile, Arno and Majuro Atolls. On Jaluit part of the island which harboured the only runway of the atoll was washed away.

As has become evident, a series of typhoons have visited the atolls, and such events are not rare.

Table 2 Typhoons known to have affected the atolls of the Marshall Islands. Data set in italics refer to typhoons which came within at least 15nm of the geographical centre of the atoll (for coordinates used see table 1).

Year	Date	Name	Atolls affected	References
1840s			Likiep	Goetze 1914
~1850			Rongelap, Rongerik, (Ailinginae ?; Bikini ?)	Krämer & Nevermann 1938
1854			Likiep, Mejit, (Ailuk?)	Erdland 1914
1857			Ebon	Krämer & Nevermann 1938
1864	3 May		Ebon	Snow 1864
1864	early		Ujelang	Nautical Magazine 1864; Hezel 1979
1870			Ujelang	Krämer & Nevermann 1938; Witt 1881
1874			Ailinglaplap, Kili	Witt 1881; Krämer & Nevermann 1938
1875	early November		Kili, Jaluit, Namorik, Kwajalein. Ebon, (Mile ?)	Hezel 1979; Colcord 1875; Young 1877
1890			Uterik, (Taka ?)	Fosberg 1956
1891	17/18 October		Jaluit, (Kosrae)	Missionary Herald Aug 1905; Steinbach 1893b
1899			Ujelang	Krämer & Nevermann 1938
1899	January		Arno, Majuro?, Likiep	Anonymous 1900
1900	December		Ebon, Mile, Namorik	Walkup 1901
1905	30 June		Mile, Nadikdik, Jaluit, Majuro, Arno, Ujelang, Kili, Aur, Ailinglaplap	Spennemann in prep.
1909	October		Jaluit	Merz 1910a
1911			Kili	Krämer & Nevermann 1938
1911	2-3 November		Ujelang	Ebert 1912; 1924; Merz 1911a & b
1911	16/17 November		Ujelang	Ebert 1912; 1924; Merz 1911a & b
1912	January		Jaluit	Mommsen 1912
1918			Utirik	Fosberg 1955a
1918	8 November		Majuro, Arno?	Spennemann in prep.
1939			Maloelap, (Aur ?)	Spennemann 1989
1940			Eneen-Kio	Dierdorff 1943
1941	October		Eneen-Kio	Dierdorff 1943
1950			Arno	Wells 1951
1951	20-25 March	Georgia	Rongerik,Utirik,Wotho	Data provided by JTWC Guam; Fosberg 1955a; Fosberg 1956
1952	15-16 September	Olive	Eneen-Kio	Fosberg 1957
1952	28-29 December	Hester	Ailinglaplap,Ujelang	Data provided by JTWC Guam
1953	9-11 December	Doris	Jaluit,Kili,Namorik	Data provided by JTWC Guam
1957	7-11 November	Lola	Jaluit	Slough & Stalberg 1992
1957	17-18 November	Mamie	Ailinglaplap,Jabwat,Lae Jaluit	Data provided by JTWC Guam; Slough & Stalberg 1992
1958	7-9 January	Ophelia	Jaluit	Data provided by JTWC Guam; Blumenstock 1958; 1961; Blumenstock et al. 1961; McKee 1959
1963	19-22 December	Susan	Jaluit,Namu	Data provided by JTWC Guam
1964	8-10 October	Ellen	Lae	Data provided by JTWC Guam

Table 2 (ctd)Typhoons known to have affected the atolls of the Marshall Islands. Data set in italics refer to typhoons which came within at least 15nm of the geographical centre of the atoll (for co-ordinates used see table 1).

Year	Date	Name	Atolls affected	References
1967	30 August - 3 September	*Opal*	Eneen-Kio	Lee 1980
1969	*7-9 March*	*Rita*	*Namorik*	*Data provided by JTWC Guam*
1972	*4-7 October*	*Marie*	*Bokak*	*Data provided by JTWC Guam*
1972	*12-19 December*	*Violet*	*Erikup,Lib,Wotje*	*Data provided by JTWC Guam*
1977	23-27 December	*Mary*	Bikar, Utirik, Taka, Wotho (Rongerik, Kwajalein, Ujae as (*)	Morford 1977; *Data provided by JTWC Guam*
1978	*19-20 October*	*Rita*	*Bikini,Rongelap,Rongerik,Taka,Utirik (+*Lib, Maloelap, Kwajalein)	*Data provided by JTWC Guam*
1979	*2-6 January*	*Alice*	*Namorik,Namu (+*Kwajalein, Likiep (Majuro flooded))	*Data provided by JTWC Guam*
1981	*11-15 March*	*Freda*	*Kili (+*Kwajalein, Lae, Ujae, Lib, Namu)	*Data provided by JTWC Guam*
1982	*25-28 November*	*Pamela*	*Jabwat,Kwajalein,Lib,Namu,* Majuro, Arno	*Data provided by JTWC Guam*
1986	*11-13 August*	*Georget*	*Eneen-Kio*	*Data provided by JTWC Guam*
1986	*21-23 December*	*Norris*	*Kwajalein,Lae,Ujae*	*Data provided by JTWC Guam*
1987	*20-22 August*	*Ed*	*Lib,Ujelang*	*Data provided by JTWC Guam*
1987	*4-5 September*	*Holly*	*Taka,Utirik*	*Data provided by JTWC Guam*
1988	*8-9 January*	*Roy*	*Namu* (+Kwajalein, Lib, Arno, Majuro, Maloelap)	*Data provided by JTWC Guam*
1990	*5-9 November*	*Page (*)*	*Kwajalein,Ujae*	*Data provided by JTWC Guam*
1990	*14-24 November*	*Owen*	*Ailinglaplap,Likiep,Wotho*	*Data provided by JTWC Guam*
1991	*4-5 November*	*Verne (*)*	*Ailinglaplap,Jabwat*	*Data provided by JTWC Guam*
1991	*17-24 November*	*Yuri (*)*	*Jaluit,Kili,Namorik*	*Data provided by JTWC Guam*
1991	*28 November–2 December*	*Zelda* (**)	*Lae,Lib,Ujae,* Kwajalein, . Maloelap, Wotje, Arno, Aur, Namu,	*Data provided by JTWC Guam;* Slough & Stalberg 1992
1992	*7-9 January*	*Axel*	*Kili;* Arno, Mile, Jaluit, Majuro, Ailinglaplap, Ebon, Namorik	*Data provided by JTWC Guam;* pers. obs. D Spennemann (Majuro), Slough & Stalberg 1992
1992	*5-7 February*	*Ekeka (*)*	*Jamo,Ujelang*	*Data provided by JTWC Guam*
1992	*5-8 August*	*Kent (*)*	*Likiep*	*Data provided by JTWC Guam*
1992	*21-22 September*	*Val (*)*	*Jaluit*	*Data provided by JTWC Guam*
1992	*6-12 October*	*Zack (*)*	*Ujelang*	*Data provided by JTWC Guam*
1992	*15-16 October*	*Brian (*)*	*Wotho*	*Data provided by JTWC Guam*
1992	*17-20 November*	*Gay*	*Ailuk;* Wotho, Uterik, Taka, Mejit, Likiep, Wotje,	*Data provided by JTWC Guam*

(*) Severe tropical storms ?. (**) severe tropical storm, developed into a typhoon after leaving the Marshalls.

Table 3. The atolls of the Marshall Islands and the years of known typhoons affecting them. Less severe typhoons, or severe tropical storms are shown in brackets.

Atoll	Latitude	Typhoon occurrences on record for
Ailinginae	11°10'	1850?
Ailinglaplap	7°26'	1874, 1905, 1952, 1957, 1990, 1991, 1992
Ailuk	10°20'	1854?, 1992
Arno	7°10	1899, 1905, 1918, 1950, 1982, (1988), (1991), 1992
Aur	8°12'	1905, 1939, 1991
Bikar	12°15	1977
Bikini	11°30'	1850?, 1978
Bokak (Taongi)	14°32'	1972
Ebon	4°38'	1857, 1864, 1875, 1900, 1905, 1992
Eneen-Kio (Wake)	19°18’	1940, 1941, 1952, 1967, 1982, 1992
Enewetak	11°30'	
Erikup	9°08'	1972, 1992
Jabwat	7°44'	1957, 1982, 1991
Jaluit	6°00'	1875, 1891, 1905, 1909, 1912, 1953, 1957 (2), 1958, 1963, 1991, 1992 (2)
Jamo	10°7'	1992
Kili	5°37'	1874, 1875, 1911, 1953, 1981, 1991, 1992
Kwajalein	9°00'	1875, (1977), 1978, 1979, 1981, 1982, 1986, 1990, 1991, 1992
Lae	8°56'	1957, 1964, 1981, 1986, 1991
Lib	8°21'	1972, 1981, 1982, 1987, 1988, 1991
Likiep	9°54'	1840s, 1854, 1899, 1979, 1990, 1992
Majuro	7°3'	(1899), 1905, 1918, 1979, 1982, (1988), 1992
Maloelap	8°40'	1905, 1939, 1978, (1988), 1991,
Mejit	10°17'	1854, 1992
Milli	6°05'	(1875), 1900, 1905, 1992
Nadikdik	6°20'	1905
Namo	7°55'	1963, 1979, 1981, 1982, 1988, 1991
Namorik	5°37'	1875, 1900, 1953, 1969, 1979, 1991, 1992
Rongelap	11°19'	1850, 1978
Rongerik	11°20'	1850, 1951, 1977, 1978
Taka	11°18'	(1890), (1918), (1951), 1979, 1978, 1987, 1992
Ujae	9°00'	1977, 1981, 1986, 1990, 1991
Ujelang	9°50'	1864, 1870, 1899, 1905, 1911 (2), 1952, 1987, 1992, 1992
Utirik	11°12'	1890, 1918, 1951, 1977, 1978, 1987, 1992
Wotho	10°05'	1951, 1977, 1990, 1992 (2)
Wotje	9°26'	1972, 1991, 1992

Table 4. Number of typhoons affecting the atolls of the Marshall Islands. For raw data see table 3.

Atoll	Nº of typhoons 1850—1900	Nº of typhoons 1901—1950	Nº of typhoons 1951—1992	Total nº of typhoons 1850—1992	Highest Frequency/ 50 year group
Ailinginae	1	—	—	1	1
Ailinglaplap	1	1	5	7	5
Ailuk	1	—	1	2	1
Arno	1	2	5	8	5
Aur	1	1	1	3	1
Bikar	—	—	1	1	1
Bikini	1	—	1	2	1
Bokak (Taongi)	—	—	1	1	1
Ebon	4	1	1	6	4
Eneen-Kio (Wake)	—	2	4	6	4
Enewetok	—	—	1	—	—
Erikup	—	—	2	2	2
Jabwat	—	—	3	3	3
Jaluit	2	3	8	13	8
Jamo	—	—	1	1	1
Kili	2	1	4	7	4
Kwajalein	1	—	9	10	9
Lae	—	—	5	5	5
Lib	—	—	6	6	6
Likiep	3	—	3	6	3
Majuro	1	2	4	7	4
Maloelap	—	2	3	5	5
Mejit	1	—	1	2	2
Milli	2	1	1	4	2
Nadikdik	—	1	—	1	1
Namo	—	—	6	6	6
Namorik	2	—	5	7	5
Rongelap	1	—	1	2	1
Rongerik	1	—	3	4	3
Taka	1	2	4	7	4
Ujae	—	—	5	5	5
Ujelang	3	3	4	10	4
Utirik	1	2	4	7	4
Wotho	—	1	4	5	4
Wotje	—	—	3	3	3

Typhoons in the Marshalls and the El Niño phenomenon

The waters of the south-eastern equatorial Pacific undergo a quasicyclic phenomenon with a moving time interval of 3 to 5 years. During these effects, which have been termed the El Niño/Southern Oscillation (ENSO), global atmospheric disturbances develop. A great number of physical effects are associated with the ENSO, among them:

1) elevated seawater temperatures;

2 calmer seas; and

3) lowered sea-level in the centre of the ENSO affected area

(William & William 1990; Glynn 1988; Quinn *et al.* 1987; Graham & White 1988). A rise in the atmospheric temperature and the sea-surface temperature will generate climatic conditions favourable to more frequent and also more severe storms (Holland *et al. 1988*; Love 1988; Stark 1988). The sea surface temperature stands in direct correlation with the minimum sustainable pressure (and hence intensity) of tropical cyclones/typhoons (Emanuel 1987; Wendland 1977) Thus an increase in sea surface temperature, either during ENSO events or as a result of Greenhouse-gas induced Global warming, is likely to

a) facilitate the occurrence of typhoons in areas hitherto not affected,

b) shift the area of typhoon generation further eastward into the central Pacific,

c) increase the frequency of storms and typhoons; and

d) increase the severity of typhoons in areas already affected by typhoons

(Revell & Goulter 1986). An increase in the sea surface temperature of 2°C could increase typhoon intensities by 20%, wind gust velocities by 11% and wind loadings on buildings and other structures by 20% (Stark 1988). It is likely that during times of ENSO events a greater number of tropical depressions and typhoons are likely to affect the Marshall Islands. In addition, it has been argued that an increase of sea-surface temperatures of 2°C could mean an increase in typhoon frequency in the order of two to three times the present frequency (Wendland 1977).

Table 5. El Niño events since 1850 and the occurrence of typhoons in the Marshall Islands.

Year	El Niño	Strength	Typhoon
1850	yes	M	yes
1852	yes	M	
1854	yes	M	yes
1857-58	yes	M	yes
1860	yes	M	
1862	yes	M-	
1864	yes	S	yes(?)
1866	yes	M+	
1867-68	yes	M+	
1870	*no*		*yes*
1871	yes	S+	
1874	yes	M	yes
1875	*no*		*yes*
1877-78	yes	VS	
1880	yes	M	
1884	yes	S+	
1887-89	yes	M/M+	
1890	*no*		*yes*
1891	yes	VS	yes
1897	yes	M+	
1899-1900	yes	S	yes
1902	yes	M+	
1904-05	yes	M-	yes
1907	yes	M	
1909	*no*		*yes*
1910	yes	M+	
1911-12	yes	S	yes (2)
1914-15	yes	M+	
1917	yes	S	
1918	*no*		*yes (2)*
1923	yes	M	
1925-26	yes	VS	
1930-31	yes	S	
1939	yes	M+	yes
1940-41	yes	S	yes(2)
1943	yes	M+	

Table 5 ctd. El Niño events since 1850 and the occurrence of typhoons in the Marshall Islands.

Year	El Niño	Strength	Typhoon
1950	*no*		*yes*
1951	yes	M-	yes
1952	*no*		*yes (2)*
1953	yes	M+	
1957-58	yes	S	yes (3)
1963	*no*		*yes*
1964	*no*		*yes*
1965	yes	M+	
1967	*no*		*yes*
1969	yes	M-	yes
1972-73	yes	S	yes (2)
1976	yes	M	
1977	*no*		*yes*
1978	*no*		*yes*
1979	*no*		*yes*
1981	*no*		*yes*
1982	*no*		*yes*
1982-83	yes	VS	
1986	*no*		*yes (2)*
1987	yes	M	yes (2)
1988	*no*		*yes*
1990	*no*		*yes (2)*
1991-92	yes	S	yes (10)

There is circumstantial evidence to link the 1905 typhoon event to the El Niño event. The German Imperial Government's physician Schwabe mentions in his quarterly report that the wind patterns in early 1905 were different than usual: the NE trade winds blew until June. He speculates that the typhoon incident which occurred on the last day of the report period may be related to this shift in wind patterns (Schwabe 1905b).

Let us investigate the extent to which the occurrence of typhoons in the Marshall Islands coincides with the El Niño phenomenon. Quinn and Neal (1992) published a list of documented El Niño events from 1525 to the present. Table 4 shows the breakdown of the known typhoon frequency by island, while table 5 shows the years for which El Niño events were recorded, their strength and the occurrence of typhoons in the Marshall Islands.

Based on a Pacific-wide evaluation, the mean typhoon frequency in areas of the Marshall Islands is said to be 1 yr^{-1} (Holland *et al.* 1988).

The observed typhoon frequency has been computed since 1850. It is clear from the discussion on the historic typhoon occurrences, that the available data set is incomplete. Thus the typhoon frequencies provided in the table are best case estimates.

Statistical Analysis Of Association

The association between typhoon occurrence and El Niño events can be assessed by comparing the probability p_E of a typhoon occurring in an El Niño year, with the probability p_N of a typhoon in a non-El Niño year. Ideally this would be carried out by comparing the observed proportion of El Niño years where a typhoon occurred, with the observed proportion of non-El Niño years where a typhoon occurred. Such data, however, are not available due to the incomplete observation of typhoons prior to 1945. An alternative is to base the comparison on data recorded since 1945, however, this would ignore a substantial amount of information contained in the pre-1945 data. In particular, although there is no information about the absolute magnitudes of p_E and p_N in the pre-1945 data, there is substantial information about their relative magnitudes. Instead we propose a simple model, and fit the model to the observed data.

It is supposed that prior to 1945, a typhoon was recorded with probability p, while subsequent to 1945, all typhoons were recorded. Furthermore, the occurrence of a typhoon in a given year is assumed not to influence the occurrence of a typhoon in any other year and the probabilities p, p_E and p_N are assumed not to vary over time. Under this model the observed data reduce to: X_E and X_N, the number of post-1945 typhoons recorded in El Niño years and non-El Niño years respectively; Y_E and Y_N, the corresponding number of typhoons prior to 1945; M_E and M_N, the number of post-1945 El Niño years and non-El Niño years respectively; and N_E and N_N, the corresponding number of years prior to 1945. Furthermore, X_E and X_N have Binomial distributions with parameters (M_E, p_E) and (M_N, p_N) respectively, while Y_E and Y_N have Binomial distributions with parameters (N_E, $p_E p$) and (N_N, $p_N p$) respectively.

Table 6 contains data extracted from Table 5, giving the number of typhoons occurring in El Niño and non-El Niño years. Perusal of Table 6 suggests that typhoons have been occurring with greater frequency in El Niño years. In particular, since 1945, typhoons have occurred in 9 out 14 El Niño years, but in only 12 out of 34 non-El Niño years. A similar discrepancy occurs prior to 1945 (14/42 versus 5/53), however, as has been noted, this period is subject to incomplete observation of typhoons.

The three unknown quantities p, p_E and p_N, are estimated by the method of maximum likelihood using the EM-algorithm for incomplete data (Dempster *et al.*1977). The hypothesis of interest is $p_E = p_N$, that is that there is no association between the occurrence of typhoons and the El Niño phenomenon. This is tested using a likelihood ratio test on one degree of freedom (Rao, 1973). The adequacy of the model is assessed by comparing the observed typhoon frequencies with the expected frequencies under the fitted model, using the chi-square goodness of fit test on one degree of freedom (Rao, 1973).

The probability of a typhoon occurring in an El Niño year (p_E) is estimated to be 0.713 (95% CI: 0.487-0.938), while in a non-El Niño year this probability (p_N) is estimated to be 0.265 (95% CI: 0.132-0.397). Thus we estimate that typhoons are 2.691 (95% CI: 1.256-4.126) times more likely in El Niño years. The difference between the two estimates is highly significant (P=0.0026), indicating a significant association between El Niño events and the occurrence of typhoons. As a by-product of the analysis we also obtain an estimate of the proportion of typhoons recorded prior to 1945 (p), which is 0.453 (95% CI: 0.238-0.668). The expected typhoon frequencies under the fitted model were found not to differ significantly from the observed frequencies (P=0.237), indicating an adequate fit to the data.

Table 6 Observed frequencies of years where a typhoon affected atolls of the Marshall Islands, broken down by period and the presence of an El Niño event.

	El NiñoYears		*Non-El Niño Years*	
	typhoon	no typhoon	typhoon	no typhoon
pre-1945	14	28	5	48
post-1945	9	5	12	20

Implications for Preventive Measures

The observed statistical association between the occurrence of typhoons in the Marshall Islands, and the El Niño/Southern Oscillation phenomenon has a number of implications. In the light of destruction caused by the 1992 typhoons (an El Niño year) and a 71% chance of typhoons occurring in El Niño years, compared to only a 26% chance in non-El Niño years, the government of the Republic of the Marshall Islands may wish to

- step up public education programs if a new occurrence of the El Niño is established
- review housing policy to assure that all new buildings, public and private, are adequate to resist typhoons;
- review the increasing destruction of coastal broadleaf forest and resulting reduction of wind breaks
- review the policy of population concentrations on island traditionally only sparsely settled, such as Ebeye and Guegue on Kwajalein, and the D-U-D area on Majuro.

Conclusions

A review of the historic record of typhoons in the Marshall Islands has shown that there is an association between the occurrence of the El Niño/Southern oscillation phenomenon and the occurrence of typhoons in the Marshall Islands. Whilst typhoons normally occur further to the east, the warming of the ocean waters around the Marshall Islands, as part of the ENSO phenomenon generates typhoons further to the west.

Historic typhoon records show that there is an association between ENSO and typhoon occurrence, with a 71% chance of typhoons happening during ENSO years, and only a 26% chance of them happening during non-ENSO years.

This has implications for planning and public safety, which the relevant authorities may wish to take note of.

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