DROUGHT

in the

PALLISER TRIANGLE

(A provisional primer*)
January 1998

* This primer was prepared by Walter Nemanishen, P.Eng., formerly a Planning Engineer with PFRA, and author of a number of papers relating to Prairie droughts and floods. The work was sponsored by PFRA's Drought Committee, with the intent to foster education and awareness among the Prairie people of the causes and drivers of historic droughts. This primer is intended to be a compendium of historic data, analysis and trends to expand the body of knowledge on this subject. Although the information in this Primer is deemed to be accurate, the opinions and interpretations are those of the author and do not necessarily represent those of the PFRA Drought Committee.

The Drought Committee welcomes feedback from readers of this primer.

Signed, PFRA Drought Committee:

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Preface

The international focus on climate change, and the adverse impacts of recent Prairie droughts, has alerted agricultural climatologists, soil scientists and water resource managers to the vulnerability of our agricultural sector in terms of weather extremes. The super El Nino now in progress has caused serious droughts in Australia, Indonesia and Papua New Guinea. Using the 1982-83 El Nino as a template, oceanographers and climatologists predict more severe storms and droughts.

Profitable farming businesses in the Palliser Triangle are just as vulnerable to drought, soil erosion and pests as they were in the 1920's and 1930's. The recent droughts have served to demonstrate that all Federal and Provincial agencies with a vested interest in drought mitigation and soil rehabilitation must be knowledgeable of the causes of historic drought and be vigilant in anticipating their future recurrence. In 1988, Gilson and Hill' admitted that governments were not heeding some of the historic lessons, particularly in farm credit and soil conservation. Conceded Dr. Hill: "We forgot a lot of those things."

In the past 15 years there have been an equal number of Prairie conferences, workshops and other initiatives relating to climate change, drought and water resource management. Also, an international conference was held in Australia in 1991, on the physical causes of drought, especially the role of El Nino. These convocations provided forums for experts to describe some of their research relating to climate change and droughts. It appears that many of the pieces of the drought jig-saw puzzle are known. These pieces now fit together to create a partial picture. The gaps indicate where research effort is still required.

Table 1: A Partial List of Recent Prairie Initiatives Relating to Climate Change & Drought

Date	**Location**	**Initiative**	**Primary Sponsor(s)**
1983	Regina	Drought Workshop	PFRA, Cdn Climate PI'ng Brd
1983	Hanna	WATER: The Prairie's Hope	PAWM*
1986	Calgary	Moisture Management in Crop Production: Managing Drought	Alberta Agriculture
1986	3 Provinces	Prairie Drought Study	PFRA
1986	Edmonton	Impact of Climate Variability & Change: Cdn Prairies	CCC*, EC*, Alta,
1986	Regina	DROUGHT: The Impending Crises?	NRC*, Univ. of Regina (UofR)
1988	-Saskatoon	Prairie Drought Workshop	PFRA, NHRI*, SRC* & CCC*
1990	Calgary	Impact of Climate Change & Variability on the Great Plains	CCC, IWD*, NOAA*, USDC*, Univ. of Nebraska
1992	Calgary	Palliser Triangle Global Change Project	EC, GSC*, PFRA, UofCalgary, UofR, UofMan., UofWaterloo
1993	Saskatoon	1 st meeting of the Long-Range Weather & Crop Forecasting (LRW&CF) Work Group	CWB*, EC, CGC* & PFRA
1993	Regina	Palliser Triangle Global Change Project	EC,GSC*, PFRA, UofC, UofR, UofM, UofWestern Ontario
1995	Winnipeg	2nd meeting of the LRW&CF Work Group	CWB, EC, CGC & PFRA
1995	Edmonton	Prairie Climate, Landscape & Vegetation Change	CFS & Geog Dept, UofAlberta
1996 & 1997	Saskatoon	Canadian Association of Geographers (CAG)	CAG, UofSask., & others
1996	Edmonton & Saskatoon	Prairie Climate Workshops (Prairie Adaptation Study)	EC, AEP*, PFRA, SRC, UofLethbridge
1997	Wpg, Regina, & Calgary	Climate Prediction Workshops	Cdn Inst Climate Studies & PFRA
1997	Montreal	3rd meeting of the LRW&CF Work Group	CWB, EC, CGC & PFRA

*PAWM denotes Prairie Association for Water Management: CCC, Canadian Climate Centre: EC, Environment Canada: NRC, National Research Council: UofR, Univ. of Regina: NHRI, National Hydrology Research Institute: SRC, Sask. Research Council: NOAA, National Oceanic, Atmospheric Administration: USDC, United States Dept. of Commerce: GSC, Geol., Survey of Canada: UofC, Univ. of Calgary: CWB, Canadian Wheat Board: CFS, Canadian Forest Service: CGC, Canadian Grains Commission: AEP, Alberta Environmental Protection:

This report is intended to be a primer on Palliser Triangle droughts. It draws extensively upon the climatological research results of the investigators associated with the various Canadian agencies who have contributed to the initiatives listed in Table 1. Since it is now apparent that Palliser Triangle droughts are caused by teleconnections to global ocean temperatures and to atmospheric circulation patterns, the drought research results of many international scientists are also highlighted in a attempt to coherently and scientifically illustrate and explain:

- the vulnerability of Palliser Triangle agriculture to drought;
- the drought driving forces: El Nino, Southern Oscillation and solar radiation;
- the primary drought areas of the Canadian Prairies and their climate;
- the suspected origin of historical droughts, their link to the drought drivers and the threat posed by global warming; and
- the technical feasibility of drought prediction in the Palliser Triangle.

Although it has been the scourge of mankind for millennia, only in the last two decades has science been able to identify and explain how distant ocean temperature anomalies, like the El Nino, and atmospheric processes, like the Southern Oscillation, interact to create droughts in the Palliser Triangle of the Canadian Prairies. To effectively summarize and communicate this scientific understanding in a short technical report is a daunting task. Faced with a somewhat similar and difficult assignment in 1995, that of reporting on global warming, Dr. Gordon McBean, (Assistant Deputy Minister of Atmospheric Environment Services) cautioned:

"Perhaps one of the most difficult tasks facing the science community is not that of reducing uncertainty, but of properly assessing what we do and do not know and communicating such assessments to politicians and decision makers (and society in general) in a language that they can understand. Communication of this kind is also a risky business, since it often draws the ire and scorn of those who feel the science has been over simplified and uncertainties trivialized, while still confusing, even paralysing decision makers with scientific jargon."

Throughout the Primer, I use the term "average" rather then the term, "normal", being in full agreement with Gribbin's and Lamb's' conclusion that, "The first and most important lesson of the historical record is that there is no such thing as a climate 'normal' in the sense that the word was used 50 or more years ago".

Acknowledgements
Many scientific and technical experts contributed to the preparation of this Primer. The format and general contents were established by the PFRA Drought Committee members identified on the title page. Copies of recent reports and articles on global warming, climate change, droughts, El Nino, the Southern Oscillation, the Pacific North America index and solar cycles were provided by Ted O'Brien (PFRA), Allan Stewart (PFRA), Gord Bell (PFRA), Paula Brand (PFRA), Dick Bennett (AEP), Dick Hart (AEP), Rodney Jones (AEP), Ray Garnett (CWB), Dr. Madhav Khandekar (AES), Dr. Amir Shabbar (AES), Dr. Barry Bonsal (AES), Dr. S.M. McGinn (AAFC), Herb Cutforth (AAFC), Virginia Wittrock (SRC), Larry Romaniuk (WeatherTec), Tim Goos (AES), Prof. Louis Thompson (Iowa State Univ.), Dr. Laurence G. Riddle (Scripps Institute) and Dr. David Enfield (NOAA).
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Drought: Nemesis of Palliser Triangle Farmers

The Palliser Triangle, named after the British explorer Captain John Palliser, is part of the Northern Great Plains outlined in Figure 1. This vast region lies in the "rain-shadow" of the massive Rocky Mountains. The Rockies, in conjunction with the Coast Mountains, the Cascade Range and the Sierra Nevada Range, form lofty barriers to the flow of moisture from the Pacific Ocean. Moistureladen clouds from the Pacific Ocean are stripped of much of their precipitation due to cooling induced by orographic uplift as the cold lows are thrust upwards by the mountains. During winter months, the process is usually so efficient that the air masses are essentially dry by the time they skim over the final barrier, the Rockies. Rather than bringing needed moisture, the dry air mass creates only warm chinook conditions across the western portion of the Palliser Triangle.

About 35 years before Captain Palliser's exploration of the Canadian Prairie's, the American cartographer and explorer, Stephen Long, had mapped the desert region of the continental interior. Captain Palliser was familiar with this work having led an expedition through South Dakota and Wyoming, prior to his Canadian assignment. It is, therefore, not surprising that Captain Palliser correctly surmised that the semi-arid Prairie region was the northern extension of the notorious "Great American Desert". Since his 1857-1859 exploration coincided with a severe drought period, Captain Palliser cautioned that the dry region, which now bears his name, was not suitable for agricultural settlement. The research of Professor David C. Jones' into the settlement of this dry region, reveals that a number of later, but observant, Canadians supported Palliser. Commissioner G. A. French of the North-West Mounted Police, described the region southwest of Suffield (Alta) as "little more than a desert." Thus the Canadian government was adequately forewarned of the hazards dryland agriculture would face in this semi-arid region, particularly the notorious "Dry Belt" within the heart of the Palliser Triangle. Historian, Jack Gorman, aptly described this region as one of perpetual drought. Gable, a cartoonist with the Regina Leaderpost, portrayed farming in the southern Palliser Triangle as a no-win poker game against an experienced and sarcastic "Mother Nature". In one of his cartoons (Figure 2), the old lady has not only won all the farmer's money, she has even stooped to take his pitchfork and pants.

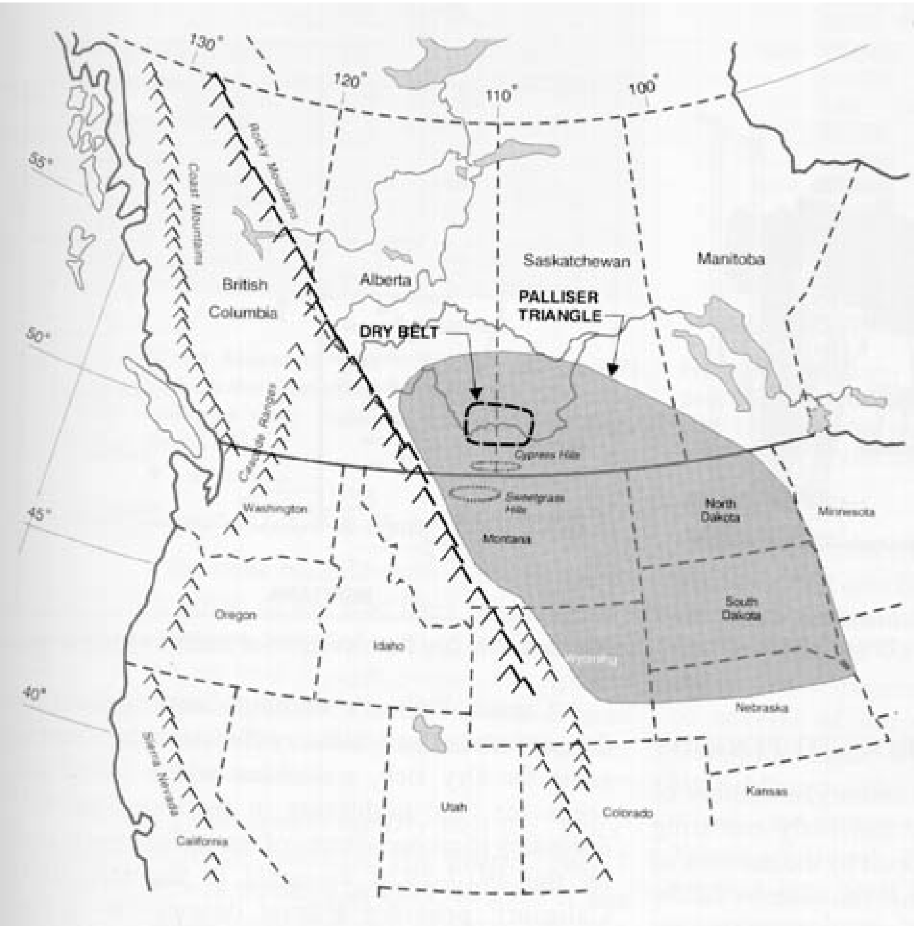


Figure 1: The Northern Great Plains (shaded area): Palliser Triangle is within Canada

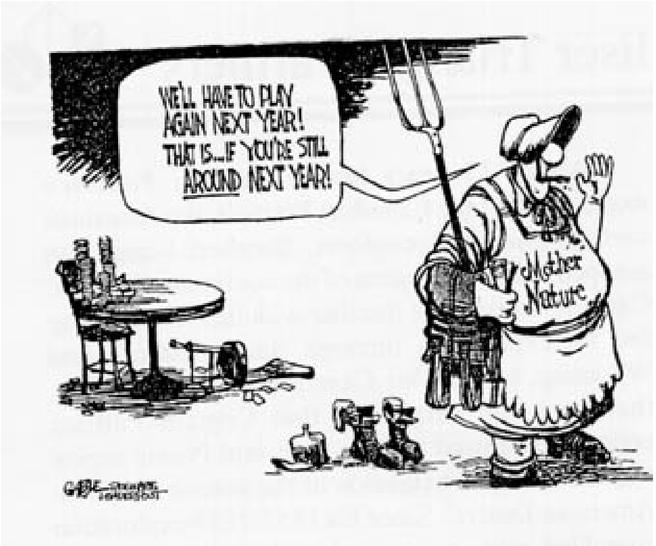


Figure 2: The perils of gambling against Mother Nature in the Palliser Triangle.

In another cartoon (Figure 3), Gable features an ex-farmer preparing to step into a lion's cage. He expresses relief for having abandoned a much more hazardous

Figure 3: Lion Taming: a profession safer than farming. (Figures 2 & 3 courtesy Brian Gable)

THREE DESTRUCTIVE DROUGHT PERIODS

By the start of the 20th century, a number of modern cropping practices and early maturing wheat strains had been developed by the network of Dominion Experimental Farms. The summer fallow system allowed the fields to bank moisture for next year's wheat crop. Even if precipitation was below average in the crop year, a good yield could be expected. But summer fallowing could not help farmers if the drought persisted into the second, and even the third, growing season. This was the terrible situation which Palliser Triangle farmers were to endure three times in the 20th century.

1. The Destructive Dry Belt Droughts: 1917-1926

Canadian geographer, Villimow', has assigned the name, "Dry Belt" to the interior of the Palliser Triangle (Figure 4). It lies in the rain shadow of the tall Rocky Mountains, the Cypress Hills, and the Sweet Grass Hills of Montana. The average annual precipitation within this notoriously drought-prone region, is less than 325 mm. Moisture losses are high due to winter chinooks and summer heat waves. In drought years, excessive heat constantly evaporates moisture from the soil. This high loss, added to the below average return of moisture in the form of precipitation, marks the Dry Belt as a region of double misfortune. Archie McKellar, who homesteaded near Bingville, (90 km north of Medicine Hat), poetically recalled the dryness of the region':

"Come and 1'll tell you a story of life on the plains, sixty miles from the Hat as the crow flies, in a land where it never rains. "

Figure 4: The Dry Belt: a region of double misfortune.

Captain Palliser's warnings were ignored by the government and railway officials in their zeal to settle the Dry Belt, a decision which sowed the seeds for "the nightmare in western Canada," according to an eyewitness of the sufferings created by the 1917-1926 droughts in the Dry Belt. Caligiuri' provides a brief description of the promotional campaigns designed to attract settlers, the consequences of the massive droughts and PFRA's efforts to rehabilitate the drought-ravaged areas within the Palliser Triangle.

In all fairness to the government and railway promoters, the land and the deceptively benign climate in the Palliser triangle were attractive to settlers. Fertile and easily broken by steam engines and powerful tractors (Figure 5), the fields initially yielded bountiful harvests. Mother Nature showered her blessings with timely rainfalls in four of the six years in the period, 1911 to 1916 (Figure 6). Bumper crops were threshed throughout the Dry Belt in 1915. In many districts, yields exceeded 40 bushels/acres. The following year was nearly as good. Farmers experienced prosperity as wheat prices soared due to overseas demands in World War 1.

Figure 5: Two Marshall gas tractors" (35-70 HP) breaking sod on the Canadian Wheatlands Company Limited holdings near Suffield, in 1913 (Glenbow Archives, NA-587-8).

Mother Nature's "Jekyll & Hyde" Personality

n 1917, the rains became mere sprinkles in the IDry Belt south of the Red Deer River. Severe drought conditions persisted until 1926. During six years, in the ten-year drought period, the April to June local rainfall did not exceed 100 mm (Figure 6). Fortunately, precipitation north of the Red Deer River was somewhat better.

Wheat yields within the Dry Belt fell. Jones records that in the Medicine Hat district, only 7 bushels/acre was threshed in 1917; in 1918 it was down to 1 bushel/acre and zero in 1919. The next two years were hardly better; yields only averaged 5 and 3 bushels/acre respectively.

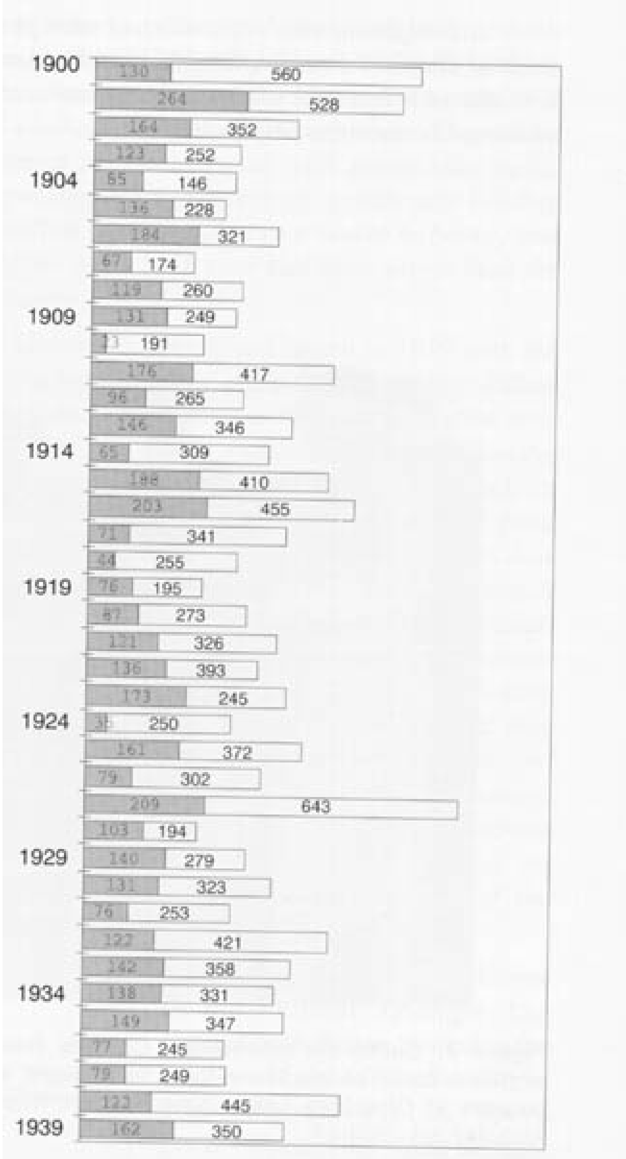


Figure 6: Growing season (Apr-June) and annual precipitation (in millimetres) recorded at Medicine Hat, 1900 to 1939. (Graph replotted from the MEDICINE HAT NEWS, Thursday, March 24, 1988).

Four years into the drought, desperate Medicine Hat area farmers and agricultural officials agreed to retain California rainmaker, Charles M. Hatfield (Figure 7). Jones gleaned accounts from the local newspapers to piece together a description of several of the secret methods employed at Chappice Lake, 60 km northeast of the city. Hatfield's apparatus included a tower, the height of which one reporter compared to the legendary Tower of Babel. His operations encompassed several Dry Belt localities in Saskatchewan according to Jones. In 1921, the Secretary Treasurer of Village of Prelate wrote to the Minister of Agriculture in Regina, of the hope Hatfield had brought to drought-weary farmers:

"... I might say that regardless of what people think of Hatfield 1 really thought that his coming here this year has kept some people in this country who would otherwise

Figure 7: California rainmaker, Charles Hatfield, explains some of his techniques to drought weary farmers at Chappice Lake, June 5, 1921 (Glenbow Archives, NA-2003-67).

The early drought years in southwest Saskatchewan prompted some naive, but high ranking, government officials to attribute the crop failures to bad farming. One such official boasted that he was convinced drought was a controllable factor in crop production and that there was no necessity for complete failure. Some "experts" recommended excessive surface tillage of summer fallow fields to create a dust-mulch to reduce evaporation. Farmers who adopted this unscientific advice, were the first to see their topsoil blown away by the unrelenting dust storms.

Wheat Farming Ends in the Southern Dry Belt

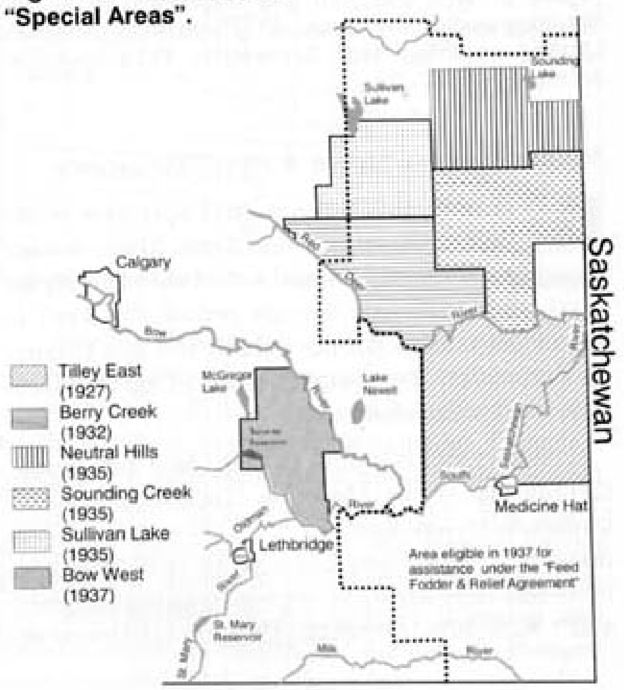
Ben Russell, an engineer with the Reclamation Service of the Department of the Interior, (and later, PFRA's first Chief Engineer) carefully documented the Dry Belt drought conditions in a 1924 report'°.

But he made no attempt to suggest any cause for the severe drought period. He does however deserve credit for admitting that the government, and others, had knowledge of the dry nature of the region prior to promoting settlement:

"7t has long been recognized that throughout extensive areas in Southern Alberta the precipitation is insuff cient for the growth of crops. From a study of the precipitation records during the past thirty five years and the financial condition of the large majority of the farmers living throughout the dry belt, it must be conceded that much of the area is more suitable for ranching than farming purposes. Due to continued drought many farmers have already been forced to abandon their farms and the prospects are that this general abandonment by farmers of the semi-arid lands will continue. "

By the time he had completed his report, Russell states that only 645 farmers were still surviving (within the survey area) of the original 2386 homesteaders. Local municipal government had ceased to function. Gorman" describes the subsequent events leading in 1927 to the passage of "An Act Respecting the East Tilly Area" (Figure 8). Only a scant four years later, this Act became the basis of the Special Areas legislation enacted to cope with the devastation wrought north of the Red Deer River by the droughts of the Dirty Thirties.

Figure 8: The Alberta "Special Areas".



2. The "Dirty Thirties "Droughts: 1929-1937

In his memoirs, Moose Jaw district farmer, Leslie Ashton", recalls the exact month when the drought started: "In retrospect, we must now recognize that the GREAT DROUGHT ACTUALLY STARTED IN JULY 1928". A year later, the Stock Market collapsed, ushering in the Great Depression. International trade barriers contributed to a ruinous decline in wheat prices. The ten year nightmare was about to begin in all of the Palliser Triangle. It was to be Canada's worst calamity.

James H. Gray provides thumbnail sketches of conditions farm families were enduring and of the drought blasted and drifting landscape existing on February 11, 1937, when the Parliament debated a bill to amend the Prairie Farm Rehabilitation Act, passed two years earlier to establish PFRA:

"The people of the West had just survived the worst year, climatically, within living memory. Not only had 1936 been the coldest bitterest winter ever recorded but the torrid summer had seen high temperature records shattered between Winnipeg and the Rockies. Even as Mr. Gardiner spoke, the winter of 1937 had started in where the winter of 1936 had left off, presaging worse disasters to come

Life on the dust bowl farms might have been tolerable for the 200, 000 farmers and their families on dried-out relief if they had been well housed and well clothed. For the most part they shivered or sweltered in shack-houses with paper thin walls, without modern conveniences, comatosely holding to a fading hope, that next year had to be better; and for seven years each year had been worse than the one before.

The desert, which had begun in 1929 with the swirling up-drafts on the parched summer fallow from Hanna to Monarch to Cadillac to Melita, now threatened the entire Palliser Triangle. Blowing topsoil drifted like snow across the railway tracks in Alberta.lt blew from the poor land onto the good land in Saskatchewan and kept Regina, Moose Jaw and Swift Current coated with dust inside and out. It bathed Winnipeg in perpetual yellow overcast. Roads made impassable by snowdrifts in winter were drifted into impassability again with blowing topsoil in the summer. The drifts built up till they covered the fences, choked out shelterbelts and gardens, reached the roofs of the chicken houses, blew through the cracks around farmhouse windows and under farmhouse doors to drive the inhabitants out of their houses and out of the country. "

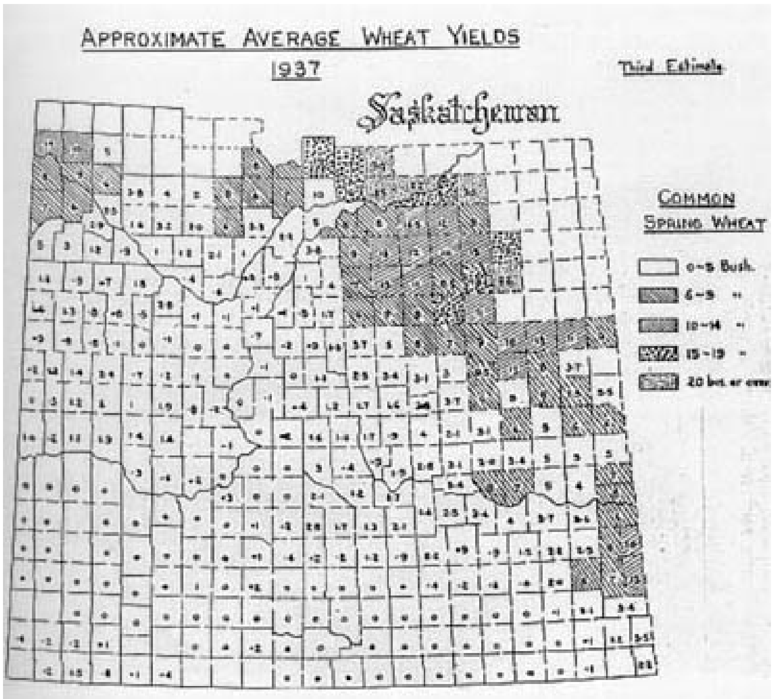


Figure 9: Average wheat yields in Saskatchewan in 1937 (reproduced from the Stapleford Report").

Despite drought conditions in the Palliser Triangle, the opposite conditions existed in the northern fringes of the Parklands, and wheat yields were good-even in the worst drought year, 1937. That year, the southern third of the Saskatchewan wheat growing area had zero yield (Figure 9). Many destitute farmers trekked north to grub-out a new life in the bush country (Fig. 10 & I1).

Jack Gorman recalls vividly the demise of dryland farming in the northern Dry Belt. Thousand of destitute farm families were forced to abandon their homes, a tragedy he calls, "The Exodus." Many of the destitute farmers loaded their meagre belongings on wagons, old trucks and even "Bennett Buggies", named after then Canadian Prime Minister, Rt. Hon. R.B. Bennett. The

"Bennett Buggy" became a visible symbol of the Fords, and other vehicles. Ingeniously, they rigged a drought and depression in the Canadian Prairies. It, double tree and wagon pole to the front axle and therefore, deserves some description. Nearly all the hitched a team of horse to provide real "horsefarmers in the 1930's lacked money to either power" for a slow, but comfortable trip into town.

Figure 10: Bennett Buggy trek to Northern Saskatchewan. (The Provincial Archives of Alberta photo 75.334/46)

Figure 11: Chased north in the mid-1930s by drought and grasshopper plagues from their farm at Creelman, Saskatchewan, Mrs. Leitch and her three children pose in front of their log cabin. Steeled by back-breaking struggles for survival, her eldest son Merv, would eventually serve as the Attorney General, the ProvincialTreasurer, and finally the Energy Minister in the Alberta Provincial Government. His tough farm experiences in the Depression-era left him with one dominant impression: people can solve their own problems; governments can't do it for them. (The Provincial Archives of Alberta photo 75.334/56)

The Dirty Thirties' Legacy

By 1937, the elements had taken their toll. Gorman enumerates them:

"The winds, the searing heat, the drought, the weeds, the mosquitoes, the grasshoppers, the grain ***diseases*** *- smut and rust, the interminable winters, the blizzards and the sub-zero temperatures. "* Stapleford was more graphic in portraying the drought-ravaged southern Saskatchewan landscape (Figure 12): *"In the worst drought areas, indescribable scenes of desolation have taken the place of the golden fields of ripening grain, extending far away to the horizon, which in other and better days gave to the prairie the romantic name, THE GOLDEN WEST".*

Using data from the 1931 census and the 1936 census, Stapleford calculated that 66,000 people had gone elsewhere: to the other provinces, to the USA. Some weary and disillusioned homesteaders even returned to Britain.

Thousands of scraggly shelterbelts still dot the southern Prairie landscape, mute sentinels to the long abandoned farmsteads. In some remote areas, a windowless house and its companion, a sagging barn, can still be seen-like on the former Storcher homestead (Figure 13) in Special Area #2, southwest of Youngstown.

Figure 13: The Storcher homestead: once home to a happy family, it now provides shelter to a family of great horned owls which nest in the only surviving farmstead tree.

Figure 12: Cadillac (Sask.) farm abandoned because the topsoil had been lost to the desertification processes in the 1930s. In this region of southwest Saskatchewan, annual precipitation during the eight year drought averaged a scant 280 mm compared to the recent 30-yr average of about 350+ mm. (PFRA photo 32227, c. 1937).

<u>3. **The Droughts** of *the 1980's: 1983-1988*</u>

Post Dust-Bowl Era Preparations

Starting in 1935, PFRA assisted in the construction of thousands of farm water sources.

Irrigation Districts and local farmers, PFRA was also instrumental in expanding the areas irrigated in the Irrigation Districts, from 155,180 hectares in 1935, to 359,950 hectares in 1979: Topham'6 has documented the history of these projects. Some of the expansion projects, like Rolling

Eastern Irrigation District, were constructed by PFRA to resettle drought-displaced farmers from southwestern Saskatchewan.

Beginning in 1937, PFRA undertook to develop community pastures in the open-plains area where the soil and climate had been found by experience and survey to be unsuited for grain farming. The wind-eroded areas were seeded to drought resistant grasses and fences erected.
Eventually, 87 community pastures were operational, encompassing one million hectares of land that was once blowing, weed infested, abandoned and useless. These lands now provide summer pasture for 125,000 head of cattle.

While the dust was still swirling in areas of almost total crop failure, large-scale tree planting projects were launched by PFRA with seedlings provided from the Indian Head (Sask.) Shelterbelt Centre. Initially, farmers were hired to plant the seedlings under PFRA's direction. As the shelterbelts grew, they provided windbreaks to arrest soil erosion, refuge for wildlife and beauty and shelter for the farmsteads.

To assist in the rehabilitation of the drought areas of southwest Saskatchewan, PFRA constructed dozens of large storage reservoirs and nine separate projects enabling farmers and ranchers to irrigate in excess of 16,000 hectares. The crown jewel of PFRA's engineering achievements was the construction of Gardiner Dam, one of the largest earth dams in the world. This structure created Lake Diefenbaker, (Figure 4), a multi-purpose reservoir, which can supply water to 124,000 hectares" of potentially irrigable lands.

PFRA's ongoing Prairie soil conservation efforts were refocussed and expanded in response to the Federal Government's Senate Standing Committee's investigations on soil degradation" in 1984. The droughts of 1977 and 1980 prompted PFRA to study and document a series of land degradation and soil conservation issues in 1982 and 1983. Solutions were sought to soil salinity, soil erosion, and organic and fertility losses". As a result of this study, several new conservation accords were negotiated with the Provincial agencies. Eventually, a Permanent Cover Program was implemented which provided financial incentives to farmers to restore drought-prone marginal lands to permanent cover (Figure 14).

The "Stealthy" Approach of the 1980's Droughts
The onset of the seven-year drought period, 1983 to 1988, caught nearly all the Prairie agricultural authorities napping, despite Dr. Charles Abbot's 1938 warning to Agricultural Canada to expect the return of a similar prolonged, severe drought period in the 1980s. Fortunately, PFRA and its provincial partners had made major progress in drought proofing the agricultural sector within the Palliser Triangle with rural water pipelines (Figure 15), tank loaders and community storage reservoirs.

Blissfully unaware of the trap Mother Nature was about to spring on them, scores of Canadian and American drought experts and water resource managers convened August 29-30, 1983, at the DROUGHT WORKSHOP in Regina.

The Workshop delegates enjoyed warm and dry "Indian-Summer" weather. During two days of sessions, only a few minutes were given to drought prediction. The primary focus of the Workshop was on the definition of the phenomenon, on monitoring aspects and on documenting the impacts. Any discussions relative to drought prediction were stifled when one expert, referring to the complacency which develops in times of ample rain, intoned: "Clearly, we are a long way from being able to use climate records as a predictor of future drought." The total reference to ENSO, and the research by Dr. Jerome Namias (of Scripps Institute) on Pacific sea surface temperature, consisted of only two brief sentences-at a time when all the drought-prone areas around the world were already in the relentless grip of awesome droughts (see Figure 16), spawned by the century's most powerful ENSO event.

!, **Figure 14: Drought prone marginal land near Hanna seeded to grass under PFRA's "Permanent Cover**

Figure 15: Two Fiat Avis F040's and a Caterpillar D-8 combine their 1210 HP to plow-in a rural water pipeline across a bone-dry pasture near Milk River, Alberta (PFRA photo 615302-2). The water source for this 90+ farm distribution system is a single well shown pump tested at 250igpm. (PFRA photo 61415-2).

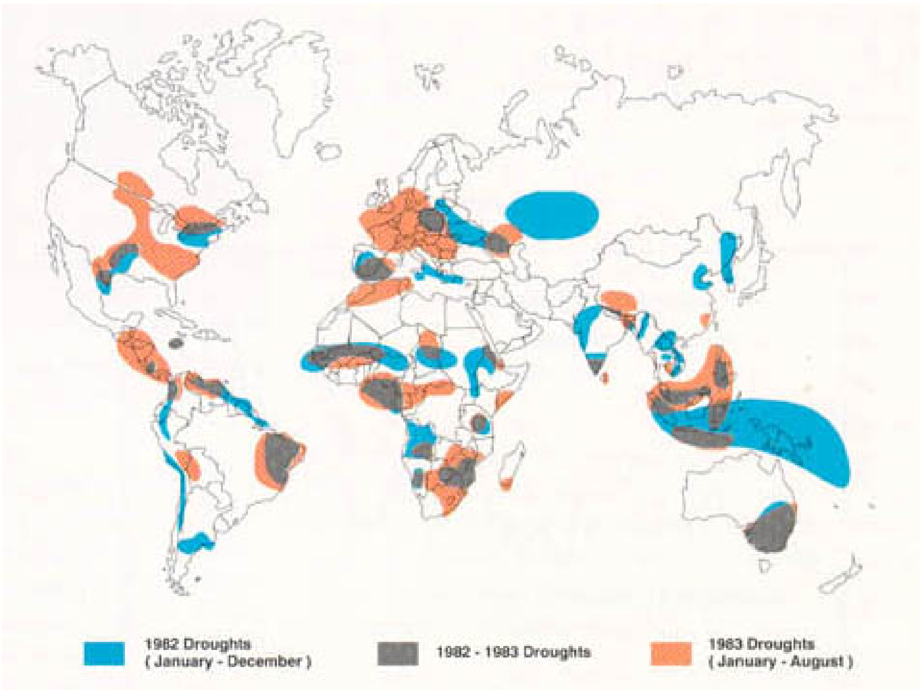


Figure 16: Worldwide occurrence of drought, January 1982 to August 1983 (reproduced from Whilhite's and Glantz [52] Figure 1).

The impacts of the subsequent drought years, and government mitigation efforts, are documented in many reports, including the PFRA Water Sourcing Studies, and Wheaton's and Arthur's report. These impacts will not be discussed in this Primer. Most farmers and ranchers managed to survive financially.

Starting in 1984, the three levels of government provided assistance to truck hay and to construct new water sources. Several income "safety-net" programs were also operational, such as the Guaranteed Revenue Income Program (GRIP) and the Net Income Stabilization Account (NISA).

Northern Great Plains' Drought Driving Forces

The physical features of Prairie droughts have been well documented by early Canadian geographers and climatologists 24 but the fundamental causes of drought were not identified. Starting with the latter stages of the 1930s and continuing for several decades, some investigators sought a direct drought-sun connection. It was not until the 1988 Prairie Drought Workshop, in Saskatoon, that attention focused on the two tropical Pacific variables which are now known to be responsible for droughts around the globe. These two variables are the El Nino and the Southern Oscillation. Although distinctly separate phenomena, they invariably act in concert, denoted ENSO.

Regardless of their global location, all droughts have two common weather factors: warmer than average regional temperatures and below average precipitation. This is well illustrated by the 10-year moving means for temperature and precipitation (Figure 17) recorded at Estevan, Sask. Although the contrast is greatest in the 1980's, the two curves intertwine during the period of record. In the cooler periods of the late 1920s, the early 1950s and early 1970s, the precipitation had been above average.

During the anomalous drought periods, the persistence of above average temperatures demands an enormous source of heat to fuel the atmosphere. At the 1963 Climate Change conference in Rome, Dr. Jerome Namias25, in discussing surfaceatmosphere interactions as the fundamental causes of drought, theorized, "... that some influences external to the atmosphere must be called upon to provide a "memory" in order to cause the persistence ... ." Dr. Namias' investigations eventually enabled him to finger the labile Gulf of Alaska cyclone 26 (commonly called the Aleutian Gyre) as the key to large-scale weather modification elsewhere. He was then able to demonstrate that the "memory" component was the anomalously warm ocean temperatures which fuelled this atmospheric heat engine. A brief description of the Aleutian Gyre, a derivative of El Nino, is provided in a later section.

In his key note address on "Drought Driving Forces" at the 1988 Prairie Drought Workshop, Dr. Eugene Rasmusson2' took time to briefly reminisce about his drought experiences:

"Among the most vivid memories of my early childhood in Kansas are the devastating droughts and dust storms of the 1930's. The most severe of those hot, dry summers, 1934 and 1936, have become the standard of comparison for all U.S. drought and heat waves. Yet, surprising as it may seem, we have yet to understand why the climate of North America was so anomalous during that particular decade. "

He then proceeded to discuss the drought drivers, beginning with the tropical ocean-atmosphere coupling and remote forcing (through persistent circulation anomalies), and concluded by mentioning external influences, like solar radiation and volcanic eruptions. Although Dr. Rasmusson's paper provides the general framework for this part of the Primer, additional relevant and/or new information is alsc highlighted.

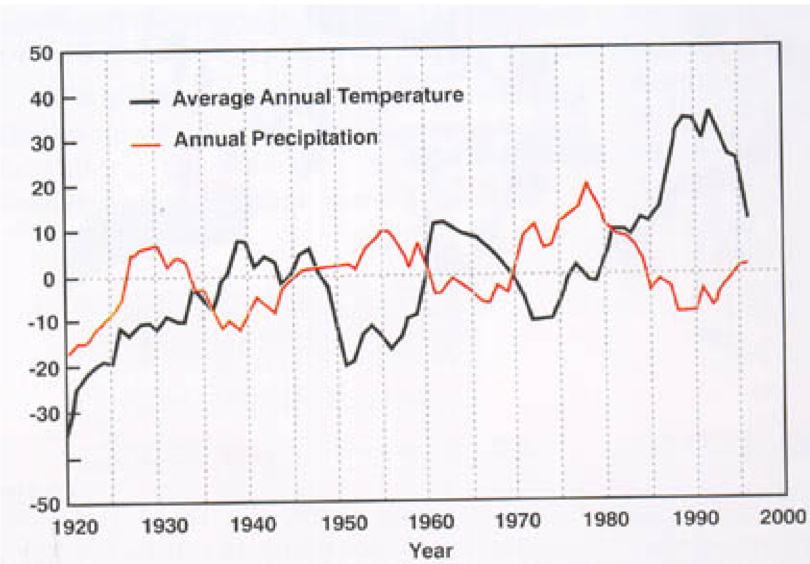


Figure 17: Ten-year, moving averages of annual precipitation and temperatures for Estevan, Sask. During warm decades, the precipitation tends to be less than average: the converse is also true.

It is now well known that there are two primary **terrestrial** drought driving forces: El Nino and the **Southern Oscillation,** which when acting in tandem, are denoted ENSO. A series of complex oceanographic and atmospheric processes form the linkages between the ENSO phenomena and destructive weather patterns around the globe, including Palliser Triangle droughts. The two linkages which have received the most scientific attention from the Northern Great Plains' drought researchers, are the Pacific-North American (PNA) low-pressure and high-pressure patterns, and the sea-surface temperatures (SST's) in the North Pacific. Researchers" have also investigated other teleconnections, (like the North Atlantic Pattern, the South American Pressure Index, the Quasi-Biennial Oscillation, the Baffin Island-West Atlantic Pattern and Eurasian snow cover), but a discussion of these parameters is beyond the scope of this Primer.

Figure 18: A violent dust storm pursues a truck along a Kansas back road, March 21, 1937 (Courtesy USDA, Soil Conservation Service).

In this Primer, solar radiation is identified as the extra-terrestrial driver, albeit, it acts somewhat behind the scenes in contributing to drought. Sunlight provides the energy to power the immense oceanographic and climatological machine. It is a well known fact that the sun exhibits cyclical features, such as the sunspot numbers and the magnetic field reversals. Furthermore, its energy output, which spans much of the electromagnetic spectrum, is not a perfect constant. Because many scientific studies of Great Plains' droughts have examined the influence of the sun, some of these results are summarized.

THE DOMINANT TERRESTRIAL DRIVERS

El Nino can be considered as the central "memory bank" in the Palliser Triangle drought process. It is the gigantic heat sink which stores the solar energy and slowly releases it to reinforce the sun's energy in powering the climate system. The vast thermal energy of El Nifio and its PNA derivatives, contribute to the persistence of drought.

Closely allied to EL Nino is the Southern Oscillation, a see-saw of air pressure between the eastern equatorial Pacific and the Indonesian region. When the surface atmospheric pressure is abnormally high over one region, it is usually abnormally low over the other.

Thumbnail sketches of the Southern Oscillation, El Nino and their linkages to the PNA processes, are provided in the next three subsections.

1. The Southern Oscillation

Meteorologists with the India Meteorological Department were the first to initiate long range drought forecasting. Their interest was the southwest monsoon. Y.P. Rao'y provides a comprehensive description of these investigations, some of which were started by 1880. Spearheading the early efforts was H.F. Blanford, then Director General of the India Observatories. Blanford was prompted to develop seasonal forecasts because of the disastrous failure of the monsoons, particularly in 1876 and 1877. His successor, Sir Gilbert Walker, continued Blanford's investigations for the same reasons. He set as his goal, monsoon prediction. In a recent paper, Khandekar" presented a synthesis of all the work to date.

The Walker Circulation

key component of the Southern Oscillation is A the "Walker Circulation" (Figure 19) named after Sir Gilbert Walker, discoverer of this circulation and other relationships between seasonal climate variations in Asia and the Pacific zone. These long distance relationships are now designated, "teleconnections".

Along the equator, the sun is either directly overhead or at a high angle since its northern and southern extreme declinations do not exceed 23 degrees, 27 minutes. Hence, the equatorial zone receives much more solar energy per unit area than the temperate zones and is the site of many dynamic, atmospheric processes. The most important process is the Walker Circulation which occurs in the vertical plane in the lower 12,000 m of atmosphere. (Khandekar illustrates the dynamic processes occurring at higher elevations in the troposphere and the stratosphere.)

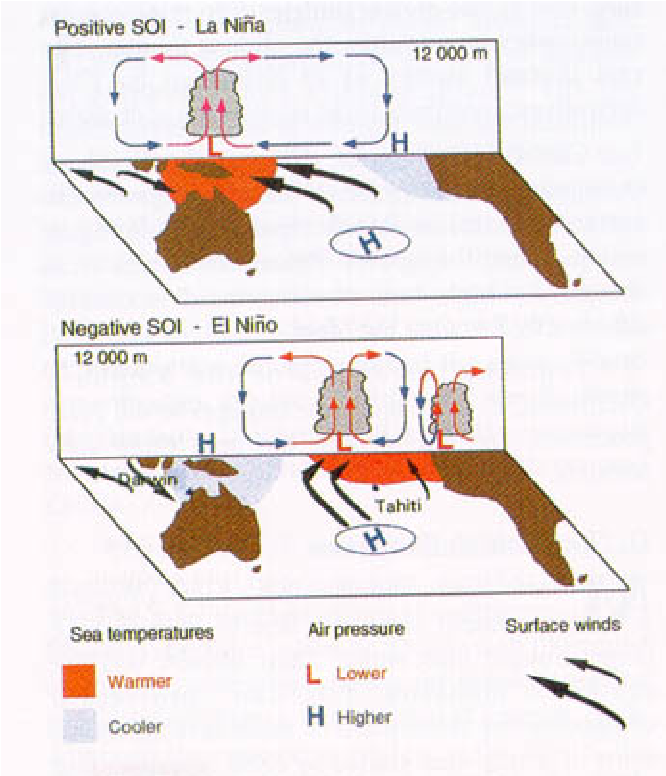


Figure 19: Walker Circulation along the equator. (Reproduced from Drosdowsky's Fig. 2.2).

Drosdowsky', identifies three main elements of the Walker Circulation:

1. air flows west across the tropics of the Pacific (south-east trade winds), being warmed and gathering moisture from the warmed waters of the western ocean;
2. it is uplifted over the Indonesian region, dropping the moisture as rain;
3. the dry air then flows east, at an altitude of about 12, 000 metres, to sink again over the normallv cold waters of the eastern Pacific.

Sir Gilbert Walker described the Southern Oscillation as the tendency of atmospheric pressure at stations in the Pacific to increase and the pressure in the region of the Indian Ocean to decrease. Scientists now attribute the Southern Oscillation to the large changes in the Walker circulation which are closely linked to the pattern of tropical Pacific sea surface temperatures, especially El Nino.

The Southern Oscillation Index

A very readable description of the Southern Oscillation Index (SOI) was recently compiled by Tribbia. The SOI is a numeric value calculates from the monthly or seasonal fluctuations in the sea level air pressure difference between Papeete Tahiti and Darwin, Australia. Records of barometric pressure at Darwin and Papeete, used to calculate the SOI, date back to 1869 and 1871 respectively. Drosdowsky's 25-year time series of monthly SOI's is reproduced in Figure 20. As expected, rainfall in eastern and northern Australia is closely correlated with high positive SOP because the easterly Walker Circulation bring moisture-laden air into this region. Drought conditions often prevail when the SOI drops below -5, because the winds are from the west and predominantly dry. Drosdowsky analyzed rainfall events during extreme positive and negative SOI years to determine the a real rainfall distribution. He found that if the SOI was below -10 in El Nino years, 63% of eastern Australia would experience below average rainfall (see Table 2). This condition persisted from 1990 to 1994, causing ruinous droughts which are graphically illustrated in the 1994 book, Australia in Crisis: THE DROUGHT

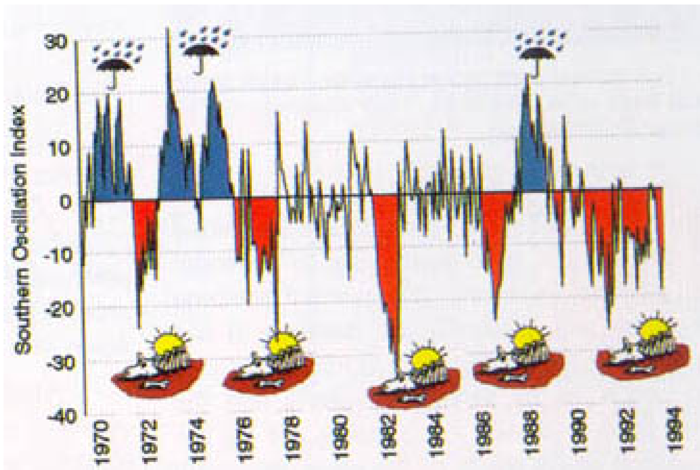


Figure 20: Monthly changes in the SOI and their impact Australian rainfall and drought. When the SOI is positive, tradewinds blow from the east bringing rainfall to Eastern Austr the opposite occurs when the SOI is negative. (Reproduced Drosdowsky's Fig. 3.1).

Table 2: Rainfall in Eastern Australia and the SOI

YearType	Average Annual SOI	Area of Eastern Austrailia receiving:	
		bl average rainfall	ab average rainfall
El Nino*	Below -10	63%	6%
La Nina#	Above +10	3%	71

*1918, 1940, 1957, 1965,1972, 1976, 1982 & 1986
#1916, 1938, 1950, 1955, 1970, 1973, 1975 & 1988

2. El Nino

Since 1983, the El Nino phenomenon has been the subject of hundreds of press articles, scientific reports and TV documentaries. Its effects on local weather and ocean circulation has been known for centuries by Peruvian fishermen but as noted by Madeleine Nash in a recent TIME" article:

"Until recently, most weather scientists paid scant attention to the periodic episodes of warm water that for countless centuries had appeared off the coast of Peru . ... it took the disastrous weather of 1982-83 to convince scientists and policy makers that the tropical Pacific merited closer watching ".

The International Geophysical Year Studies

The early 20th century work of Sir Gilbert Walker, on tropical climate fluctuations, appears to have gone unnoticed, or was soon forgotten, by western scientists. Knox" documents that it was not until after the 1957-58 International Geophysical Year (IGY) that oceanographers and atmospheric scientists again began to link local El Nino events to global variations in ocean temperatures and atmospheric circulation. Fortuitously, the IGY coincided with the strongest El Nino episode since the 1941 ENSO event.

***The Current** El Nino Interest*

In the latter half of 1997, an unusually warm El Nino developed in the eastern Pacific. It soon became apparent that this El Nino was not only the earliest on record, but possibly one of the largest of this century, exceeding the historic 1982-83 El Nino. By September 3, 1997, sea surface temperatures (SST's) along the eastern equatorial Pacific and all along the western North American coast exceeded the long-time average by 3 degree Celsius (Figure 21).

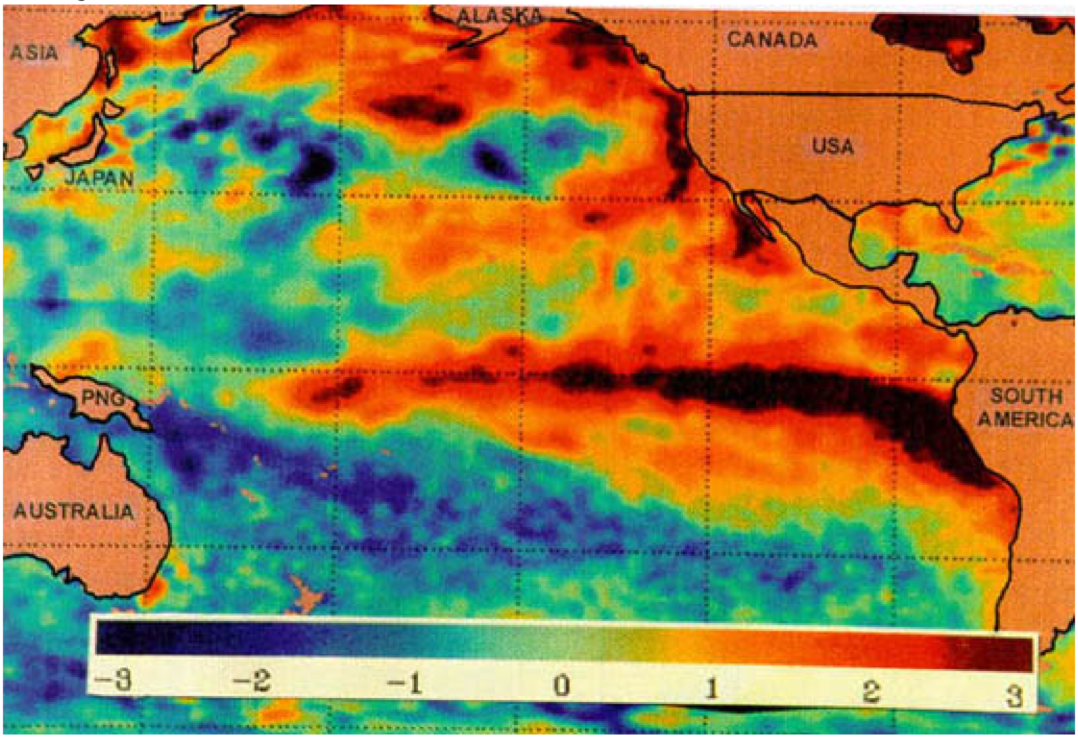


Figure 21: El Nifio SST anomalies measured Sept 3/97 by orbiting satellites (FNMOC OTIS 4.0: SST-NCEP). The highest sea surface temperature anomalies exceed 3 degrees and are shown in dark red. Lower temperature anomalies fade downwards to red, orange and yellow. Cooler than average regions are those colored in shades of blue. The Aleutian Gyre region (adjacent to Canadian west coast and Southern Alaska) is prominently outlined by the huge, horseshoe-shaped, pool of anomalously warm ocean waters.

The 1997 E1 Nino temperature extremes have again balanced much of the world on the knife edge of unprecedented natural disasters. Consequently, this El Nino became the focus of much scientific and media attention, and the topic of conversation among farmers in local cafes. Numerous Internet websites regularly feature El Nino data and information. NOAA's Climate Prediction Center site (http://nic.fb4.noaa.gov::80) provides information on historic events. The Fleet Numerical Meteorological and Oceanography Internet site (http://www.fnoc.navy.mil/) displays the SST anomaly maps.

Early in 1983, Canadian climatologist, Amir Shabbar, identified El Nino as the cause of mild winter in western Canada in 1982-83 and provided a concise scientific description of the phenomenon".

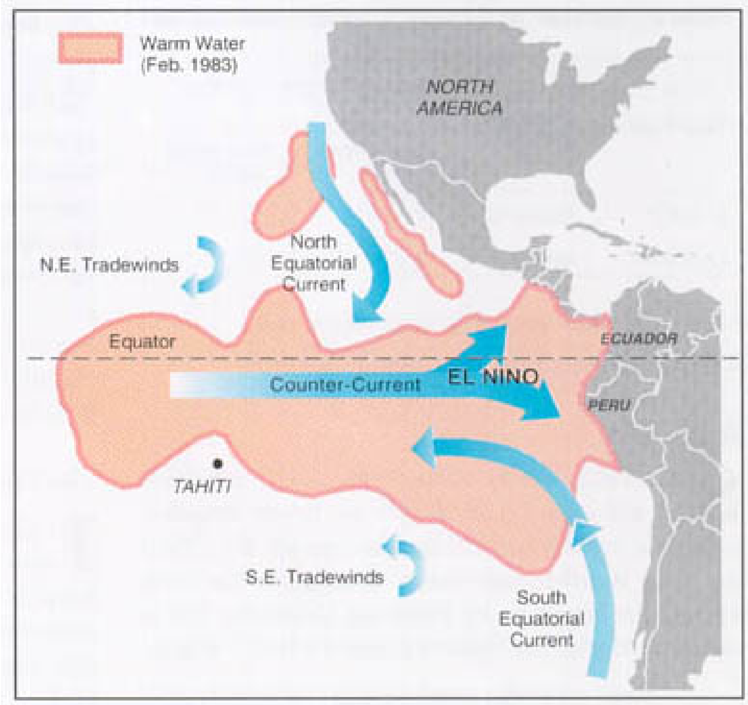


Figure 22: Ocean and air currents during the 1982-83 El Nino (map adapted from Shabbar).

Shabbar's description of El Nino is quoted verbatim in the next section as he introduces other important climate drivers, such as the Southern Oscillation and solar radiation. Although written by Shabbar in 1983, the information is still current. Other published sources, particularly the Australian bulletin on CLIMATE VARIABILITY AND EL NINO", and reports by Knox, and by Ramage" provide excellent descriptions of El Nino.

Physical Features of an El Nino

In describing the anomalous weather of 1982-83 Amir Shabbar recounted:

"Climatologists with Environment Canada and elsewhere believe that there is a common denominator explaining these confusing weather events. It is a phenomenon known as El Nino.- a weak warm coastal current that develops off Peru and Ecuador around Christmas every year and that creates a vast body of warm water in the Equatorial Pacific Ocean. Peruvian fishermen gave it the name of Corriente del Nino, in English Current of the [Christ] Child.

During most of the year, the combined action of southeasterly trade winds and the Earth's rotation maintains the cold Equatorial Current off western South America (see map). This cold current allows nutrient-rich water to upwell off Peru and Ecuador, thus providing one of the world's most productive fisheries. Every year, during the Christmas season, the warm El Nino Current moves southward off Ecuador, literally blocking the nutrients from surfacing. A decrease in the quantity of phytoplankton available to the marine food chain causes a reduction in the population of zooplankton, fish, sea birds and marine animals, but the effect is short lived.

Occasionally however, the El Nino current is very intense and prolonged. Sea-surface temperatures rise 2-3 degrees Celsius above normal in the equatorial eastern Pacific and may remain very high for as long as 18 months. Fishery yields are significantly diminished, and unusually heavy rainfall in Ecuador and Peru results in flooding. In recent times, the term 'El Nino' has come to be identified with the extreme warming of the surface waters that occur at intervals of~2 to 7 years . ...

The 1982-83 El Nino caught most scientists off guard. In contrast to earlier El Ninos, the 1982-83 event first manifested itself in the mid-Pacific rather than off Ecuador and Peru. Also, the strong easterly trade winds that usually precede El Nino were absent. Last year's El Chichon eruption compounded the problem; the Mexican volcano injected huge clouds of dust and aerosols into the atmosphere. Consequently, the satellites over the Pacific were sensing temperatures which were lower than true values.

By the end of October when warm water appeared off western South America, it was clear that an El Nino of major proportions was occurring, and, as predicted, weather patterns were affected.

Heavy rains caused flooding in Ecuador and Peru and elevated ocean temperatures resulted in the loss of a whole generation of anchovies off Peru. A high pressure area remained stagnant over the western Pacific and caused the driest season on record in Australia. In contrast, vigorous storms lashed the west coast ofNorth and South America. "

***Defining** El Nino Years*

With so much radio and TV hype and articles about El Nino, it is imperative here to interject a word of caution. Kevin Ternberth", in his lengthy scientific article, warns:

"... it has been very difficult to define El Nino or an El Nino event. The term has changed meaning; some scientists confine the term to the coastal phenomenon, while others use it to refer to the basin wide phenomenon, and the public does not draw any distinction. There is considerable confusion, and past attempts to define El Nino have not led to general acceptance. Clearly, the term El Nino covers a diverse range of phenomena. "

Trenberth quotes the El Nino definition proposed in 1983 by the Scientific Committee for Ocean Research:

"El Nino is the appearance of anomalously warm water along the coast of Ecuador and Peru as far south as Lima (12S). This means a normalized sea surface temperature (SST) anomaly exceeding one standard deviation for at least four (4) consecutive months. This normalized SST anomaly should occur in at least three (3) offive (5) Peruvian coastal stations. "

El Nino Regions

0ceanographers have divided the equatorial Pacific Ocean into four distinct Nino regions as shown in Figure 23. Nino 1+2 extends from the equator to 10 degrees south while the other three regions straddle the equator by 5 degrees. Studies by Trenberth and Hoar have shown that the key region for coupled atmospheric-ocean interactions in ENSO is in the mid-Pacific but extends further south of the equator. They have proposed a Nino 3.5 region bounded by meridians 120 to 180W and latitudes 5S to 10S.

Defining El Nino by Threshold Temperatures

Trenberth provides a careful review of the problems associated with defining a threshold temperature for El Nino, given the large variance in the annual cycle of SST's. He cautions that there is an inordinate preoccupation by many, solely on the northern winter months of ENSO. The super-strong 1982-83 and 1986-87 ENSO's continued throught the summer months into the following winter. He outlines a number of factors which must be considered to attain a balanced understanding of the ENSO phenomenon. He notes that tropics are dominated by one phase of ENSO or the other, with only brief periods of average conditions. Trenberth found that overall the best match with historical judgements was achieved for the Nino 3.4 events for a threshold of 0.4 degrees Celsius and 0.5 in Nino 3. His time series plots are reproduced in Figure 24.

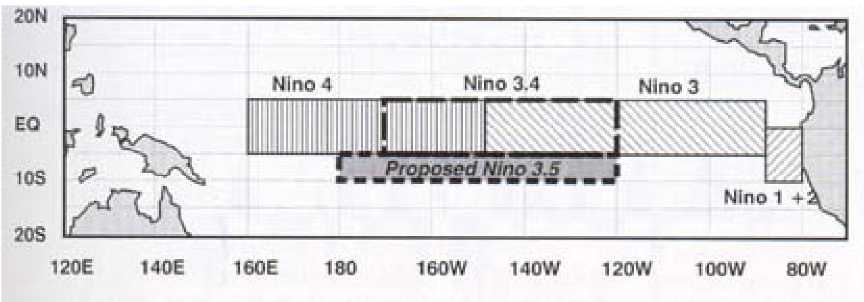


Figure 23: El **Nino regions: Trenberth and Hoar have proposed a fifth region, Nino 3.5, bounded by meridians 120 to 180W and latitudes 5S to 1 0S.**

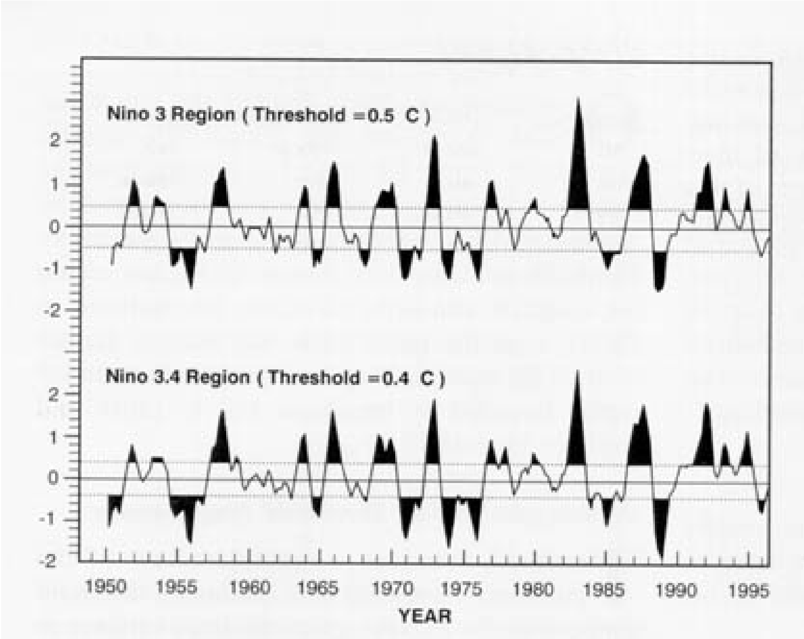


Figure 24: Five month running means of SST anomalies using data from NOAH. Shaded years indicate ENSO events.

NOAA's Internet website provides plots of historic SST's in the Nino regions since 1978 (Figure 25), but does not identify any threshold temperatures. Their website displays the Southern Oscillation Indices from 1896 (Table 4) and a Multivariate ENSO Index (MEI) from 1950 (Figure 26).

The MEI can be understood as a weighted average of the main ENSO features contained in the following six variables: sea-level pressure, the eastwest and the north-south components of the surface wind, SST, surface air temperature, and total amount of cloudiness. In order to keep the MEI values comparable, all numbers are standardized to a 1950-1993 reference period.

Historic El Ninos

Trenberth's lists of El Nino and La Nifia events are reproduced in Table 3.

Table 3: Trenberth's listing of El Nino and La Nina events after 1950 as defined by SST's in the Nino 3.4 region and exceeding 0.4 degrees Celsius threshold.

Table 3: Trenberth's listing of El Niño and La Niña events after 1950 as defined by SST's in the Niño 3.4 region and exceeding 0.4 degrees Celsius threshold.

El Niño Events			La Niña Events		
Begin	End	Duration	Begin	End	Duration
Aug51	Feb 52	7 mo.	Mar 50	Feb 51	12 mo.
Mar 53	Nov 53	9 mo.	Jun 54	Mar 56	22 mo.
Apr 57	Jun 58	15 mo.	May 56	Nov 56	7 mo.
Jun 63	Feb 64	9 mo.	May 64	Jan 65	9 mo.
May 65	Jun 66	14 mo.	Jul 70	Jan 72	19 mo.
Sep 68	Mar 70	19 mo.	Jun 73	Jun 74	13 mo.
Apr 72	Mar 73	12 mo.	Sep 74	Apr 76	20 mo.
Aug 76	Mar 77	8 mo.	Sep 84	Jun 85	10 mo.
Jul 77	Jan 78	7 mo.	May 88	Jun 89	14 mo.
Oct 79	Apr 80	7 mo.	Sep 95	Mar 96	7 mo.
Apr 82	Jul 83	16 mo.			
Aug 86	Feb 88	19 mo.			
Mar 91	Jul 92	17 mo.			
Feb 93	Sep 93	8 mo.			
Jun 93	Mar 95	10 mo.			

Table 4: SOI Ranked by Year, 1896-1995

La Niña Extreme Years from the SOI					El Niño Extreme Years From the SOI				
Rank	DJF	MAM	JJA	SON	Rank	DJF	MAM	JJA	SON
1	1974	1917	1917	1917	1	1983	1905	1905	1982
2	1918	1904	1975	1975	2	1992	1987	1982	1940
3	1929	1971	1950	1988	3	1941	1912	1987	1901
4	1904	1950	1916	1973	4	1978	1994	1940	1941
5	1976	1989	1910	1955	5	1919	1983	1941	1994
6	1951	1974	1938	1906	6	1987	1992	1994	1914
7	1939	1956	1965	1910	7	1897	1900	1965	1991
8	1989	1903	1909	1971	8	1905	1897	1896	1965
9	1971	1975	1966	1950	9	1912	1993	1972	1977
10	1956	1936	1900	1970	10	1958	1991	1977	1900
11	1917	1925	1931	1964	11	1942	1940	1914	1951
12	1943	1918	1973	1956	12	1926	1941	1993	1939
13	1962	1927	1988	1938	13	1959	1953	1911	1963
14	1930	1898	1981	1924	14	1973	1977	1923	1923
15	1950	1921	1964	1908	15	1906	1972	1925	1896
16	1921	1931	1924	1916	16	1915	1966	1946	1972
17	1925	1902	1974	1928	17	1993	1926	1951	1925
18	1967	1910	1901	1921	18	1952	1980	1976	1913
19	1910	1928	1906	1962	19	1990	1995	1919	1905
20	1922	1943	1945	1974	20	1969	1919	1953	1911

Date tabulated by NOAA, Climate Diagnostic Center (http:www.cdc.noaa.gov/-cas/year.risk.html)

In an exhaustive report, Quinn" et al., document El Nino events since the time of the Spanish exploration of South America. Their listing of very strong, strong, line of South America, the legacy of strong ENSO events has been heavy rainfall, floods, and the destruction of bridges, roads, railways, and the agricultural and anchovy harvest. Some of their results will be featured in several later parts of this primer as they provide important insight on the droughts around the time of Captain Palliser's exploration and also give a scientific hint of conditions which can be expected to occur during global warming.

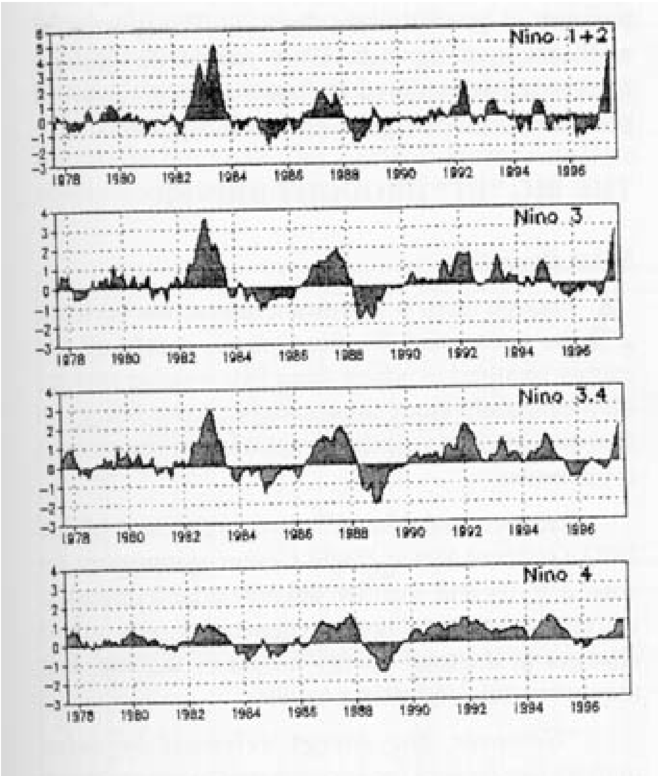


Figure 25: SST plots by NOAH in the four El Nino regions. El Nino events denoted by anomalously

Table 5: The Quinn-Neal-de Mayolo's List of El Ninos Occurring During the Last Two Centuries

Very Strong*	Strong	Moderate(M)	Wk/M
1791	1803-04	1806-07	1854
1828	1814	1812	1887-89
1877-78	1844-45	1817	1918-19
1891	1871	1819	1930-31
1925-26	1884	1821	1951
1982-83	1899-1900	1824	
	1911-12	1832	
	1917	1837,1850	
	1932	1854,1857-58	
	1940-41	1860,1866-68	
	1957-58	1874,1880	
	1972-73	1896-97,1902	
		1907,1914	
		1918-19, 1923	
		1930-31,1939	
		1943,1965-66	
		1976-77	

*A very strong El Nino occurred within a century of the year 1100 A.D., causing catastrophic floods in Peru.

3 Pacific-North American (PNA) Drivers

The 1982-83 ENSO not only caused major droughts around the world by disrupting the atmospheric circulation, it also contributed to numerous historic flood events in other regions. The drought regions are delineated in Figure 16 but not the flood-ravaged area. Just like its 1982-83 counterpart, the 1997 ENSO event has already revisited the 1982-83 drought areas and flood ravaged river basins. Large areas in the nations of Peru, Columbia and even Somalia, have been inundated in flood waters. Western parts of Mexico have been smashed by several hurricanes. Other countries, notably, Indonesia, Papua New Guinea and North Korea have again suffered drought and hunger. It is now evident that strong ENSO's cause a repetition of drought and flood events through their various derivatives. The process is similar to a giant analog computer-a comparison alluded to by Hans J. Liebscher4l of the West German Climate Change Institute.

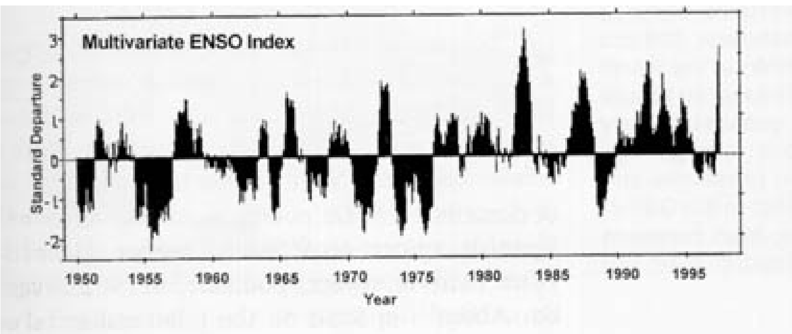


Figure 26: The Multivariate ENSO Index (MEI): it quickly toggles from positive to negative values, without a long transition period

ENSO events drive global weather events by a series of teleconnections. Investigations of the 1982-83 ENSO event by Namias, and Dickson and Livezey, clearly demonstrated that the Pacific North-America teleconnection is one of the strongest extra-tropical responses to ENSO in the world. In an earlier paper, Namias (1978) was quick to acknowledge that it was highly unlikely that the extreme 1976-77 weather events could be attributed to one causative factor. He suggested:

"*Rather, it appears that several factors operated in a synergistic fashion so that nonlinear feedback loops were set up in the earth-atmosphere system so as to force persistent recurrence of abnormalities for months at a stretch.* " One of the factors Namias fingered was the PNA Pattern.

The Pacific-North American (PNA) Pattern

A comprehensive treatise on "teleconnections", was published by Wallace and Gutzler44 in 1981. Their investigations have revealed that the most reproducible teleconnection pattern is the PNA pattern of atmospheric pressures (Figure 27) dominating four geographic centres:

A) near Hawaii (20N, 160W)
B) North Pacific Ocean (45N, 165 W)
C) Central Alberta (55N, 115W)
D) USA Gulf Coast (30N, 85 W).

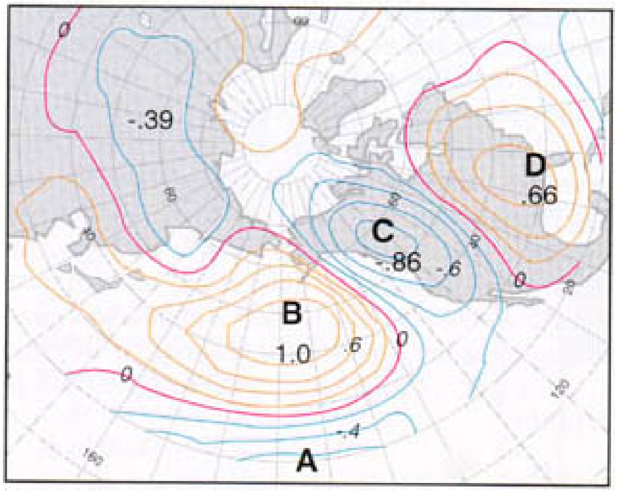


Figure 27: The winter-month, PNA Patterns outlined by cross-correlation coefficients between 500-mb height anomalies at Point B (45N, 165W) in the North Pacific with all other gridded values: based on Figure 16b in Wallace and Gutzler. This quasi-stationary pattern is typical of El Nino conditions: a large high pressure system north of Hawaii; low pressures and cyclonic circulation (counter-clockwise) in the Gulf of Alaska created by the Aleutian Gyre; high pressure system over Alberta and low pressure over the southeast USA.

The cross-correlation coefficients shown in Figure 27 were based on a 15-year record of monthly 500 mb heights for a 5 degree latitude by 10 degree longitude grid. Monthly anomaly heights were computed for each grid point by subtracting the long-term monthly height from the recorded monthly height. The correlations are with respect to Point B (in the North Pacific) which is assigned a coefficient of 1.0. A very high inverse correlation exits between the North-Pacific Centre and Point C at Lesser Slave Lake, Alberta.

Additional illustrations of the 4-Pt PNA pattern is provided in Part 3. The potential application of the 4-Pt PNA pattern to drought forecasting is explored in Part 5. A description of pressure-surface heights is given in Appendix A.

THE BIG "ET" DROUGHT DRIVER

Solar Radiation

A lthough there is a constant interaction between the ocean and the atmosphere, nearly all the energy required to power these two weather makers derives mainly from solar energy. Some energy is also provided by volcanic eruptions but the amount is unknown.

Bandeen and Maran, two organizers of the 1973 Goddard Space Flight Center symposium on solar activity and weather, acknowledged that solar activity events and cycles generated only small changes in the total energy output of the sun. But they were quick to affix a caveat:

"However, the energy released by solar activity can be very large compared to the quiet sun emission in certain restricted domains of radiation wavelengths or particle energy, and it is selectively deposited in restricted regions of the terrestrial atmosphere. Thus, the possibility exists that this energy can trigger events in those regions that in turn may influence the more energetic processes of the troposphere. " (See Hanson 46 for details of observations in the Antarctic).

Variations in Solar Radiance

A ccurate measurements of the solar radiation received at the earth's surface commenced in 1883 when six monitoring sites were established around the world. Most of the pioneering work was conducted by the Smithsonian Institute. This work is described by Dr. Charles Abbot, a renowned scientist whose professional career spanned 70 years. In his final paper published in 1963, at age 91, Dr. Abbot" reported on the relationship between solar variation and weather. His work on solar cycles led him to correctly conclude that a drought, akin to the magnitude of the 1929-1937 one, would strike the Great Plains about 1975: "There is much reason to expect such a drought beginning about 1975." The droughts of 1976 and 1977 proved him right!

A 41-year plot of monthly solar radiation intensities is presented in Figure 28. During the period shown, monthly radiation intensities (measured at the earth's surface) have varied by as much as 20% from the long-term historic average. Much of the variation can be attributed to transient volcanic dust veils created by huge eruptions. How much of the variation is attributable to solar activity events and cycles is still difficult to accurately quantify because the record from satellite observatories is too limited.

The 1883 Krakatoa volcanic eruption (documented in a special Smithsonian Institution centenary volume [41]) created a dense dust veil which persisted for three years. The reduction in solar radiation cooled the Northern Hemisphere by 0.5 degrees, creating extremely cold winters in the Northern Great Plains. Charles Marian Russell's memorable water colour painting, "Waiting For A Chinook-The Last of the 5000", provides a bonechilling picture (Figure 29) of the grim conditions during the winter of 1886 on a Montana ranch where he was working as a cowboy.

Since Dr. Abbot's pioneering work, much scientific effort has been directed to studying the possible relationships between solar activity and meteorological phenomena. The 1973 Goddard symposium was dedicated to Dr. Abbot, who attended, albeit being 101.

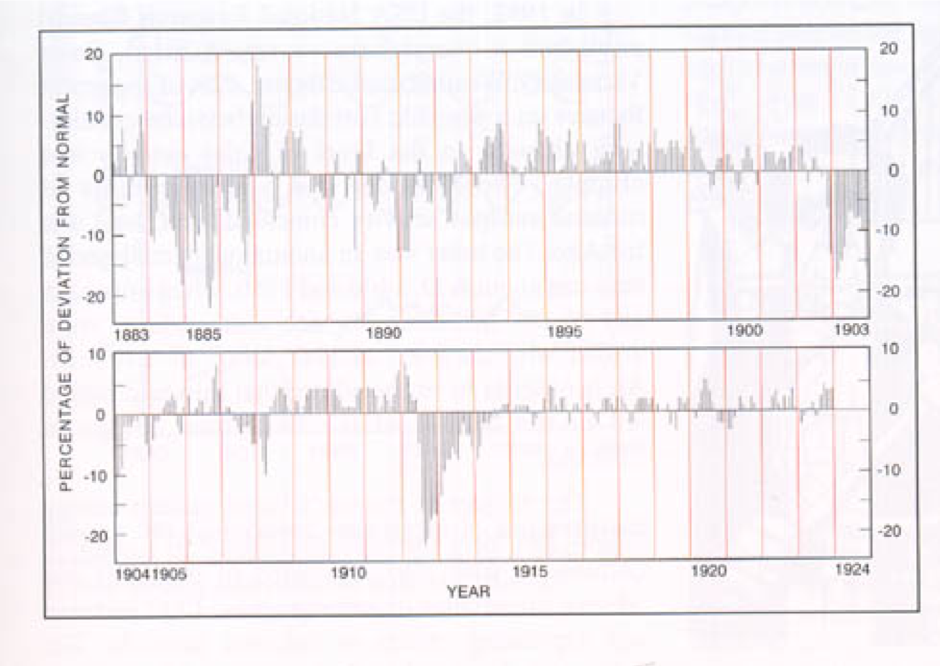


Figure 28: Solar radiation intensities measured at the earth's surface (data compiled by Kimball's). The amount of solar radiation reaching the earth's surface decreased markedly after the colossal eruptions of Krakatoa in 1883, Santa Maria in 1902 and Mount Katmai (Novaruptas°) in 1912.

Figure 29: "Waiting for a Chinook - the last of the 5000" (watercolor, 1886): C.M. Russell's, grim scene of a pack of coyotes waiting for a gaunt cow to expire on a Montana ranch during the bitterly cold winter of 1886: many exposed herds perished from mass starvation (Used with permission from the Montana Stock Growers Association, Helena, Montana).

The Goddard symposium proceedings feature 26 scientific papers on the subject, including drought on the Great Plains. In the opening invited paper, Dr. Walter Orr Roberts cited the 1972 Soviet grain deal as a example of how quickly a drought could impact world events. TIME magazine, in its August 25, 1975 issue had dubbed it the "Great Grain Robbery". This lop-sided deal stung the Americans, who could have been forewarned had their experts been monitoring Eastern European drought conditions. On a lighter note, the deal stimulated the imagination of cartoonists, like Conrad, who adapted the classic painting, AMERICAN GOTHIC, to create the cartoon, Russian Gothic (Figure 30). It featured as the farmer, then President of the Soviet Union, Leonid Brezhnev, and as the farm wife, "U.S. Wheat".

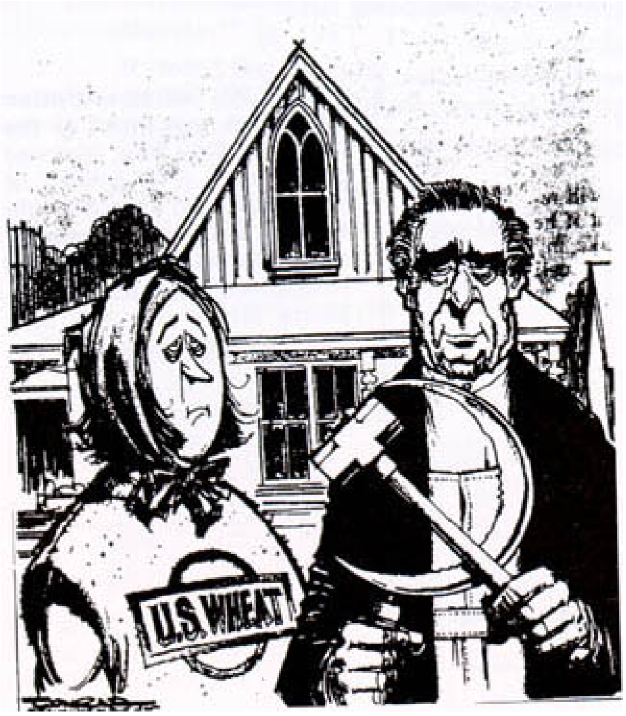


Figure 30: Russian Gothic (Conrad, Los Angeles TIMES).

Solar Activity Events and Cycles

At the 1973 Goddard symposium, Dr. Roberts piqued the interest of the assembled scientists, by featuring a sunspot-drought relationship (Figure 31) adapted from the Ph.D. thesis of Marshall". it showed that all of the major droughts came remarkably close to the solar activity minima that followed the minor peaks. He dangled an interesting comment: "It will be interesting to see what happens in this region in the period 1974 to 1978". We now know: the 1976-77

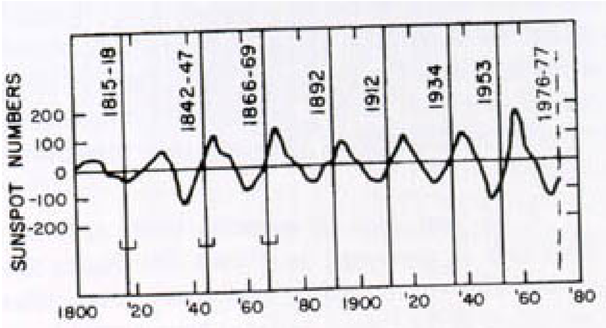


Figure 31: Great Plains' drought relation to sunspot numbers (adapted by Roberts in 1973 from Marshall). Historically, drought periods have occurred a few years after a solar minima that followed the minor peak; the droughts of 1976-77 maintained this relationship.

In 1982, the USA National Research Council published a comprehensive report titled, Solar Variability, Weather, and Climate. Part of the report focuses on a possible correlation between centurylong changes in the level of solar activity and climate. The Maunder and Sporer minima of reduced sunspot activity coincided with the Little Ice Age. The latter was an anomalously cold period between about A.D. 1400 and 1750, when European and North American surface temperatures were about one degree cooler than at present. Archeologists have speculated that this cold period led to the demise of the Norseman colony in Labrador.

The subject of the sun's facial radiant energy output, has been explored by Eddy et a152., and by Gilliland", who also attempted to elucidate the relative importance of anthropogenic C02 increase and depressing effects of volcanic aerosols. The former study concluded that the total radiative output of sun only varies by 0.2%, a value deemed too small to be significant in practical weather or climate predictions.

Gilliland's study results (graphically displayed in Figure 32) indicate that the greenhouse gases have warmed the planet by more than 0.2 degrees. Cyclical variations in solar radiation have modulated the temperatures from -0.3 to +0.3 degrees from average. Volcanic dust veils have had a greater range of temperature modulation. Massive dust veils are capable of depressing Northern Hemisphere temperature by 0.5 degrees or more.

Using a temperature prediction model, based on the external forcing parameters graphed in

Figure 32, Gilliland calculated the Northern Hemisphere temperatures from year 1800 to year 2000 (Figure 33). The model demonstrated that an anomalously warm decade greeted Palliser's 185759 expedition.

As the world enters the 21st Century, the Gilliland model predicts a sharp increase in global temperatures due to the tandem effects of the 76year solar cycle and to the greenhouse gases.

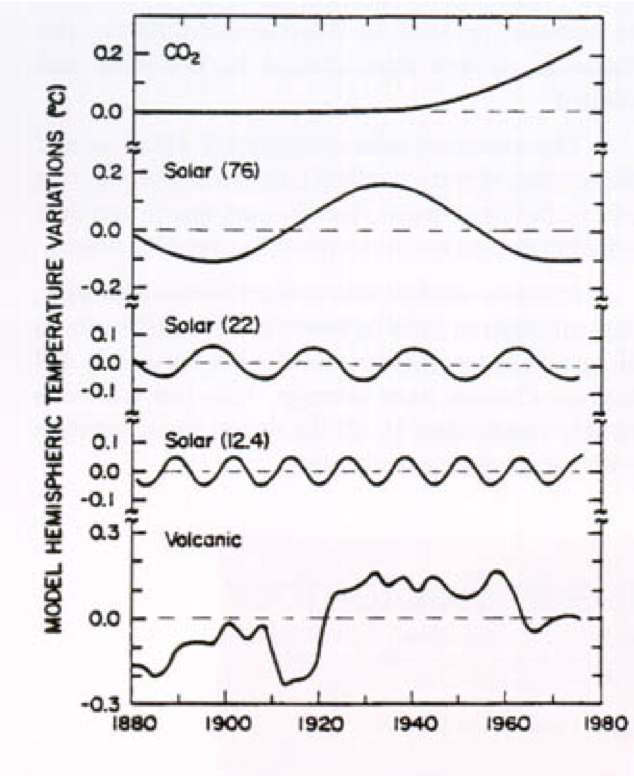


Figure 32: Computed hemispheric temperature variations for C02 forcing, 76, 22 & 12.4 year solar cycles forcing and volcanic dust veil effects.

The search for a link between solar variation and terrestrial temperatures led two researchers at the Danish Meteorological Institute to demonstrate a surprising relationship between the two variables. Eigil Friis-Christensen and Knud Lassen showed that the solar radiance has varied in phase with the 80 to 90-year period represented by the envelope of the 11-year sunspot cycle, and that this variation has caused a significant part of the changes in the global temperatures (Figure 34). In a lengthy commentary on the research, the Editors of SCIENCE advised:

"Take a good look at the graph ... . It's giving climatologists goose bumps. The curves show that when the interval between peaks in sunspot abundance began shortening at the end of the past century, the Northern Hemisphere began to warm. When the sunspot cycle stopped shortening and began lengthening around 1940, the temperatures peaked and began falling. And when the solar cycle started shortening again in the 1960s, temperature turned around too. The close association of these two curves is the most striking correlation ever found between climate and small variations in solar activity - and the strongest suggestion ever of a casual link. "

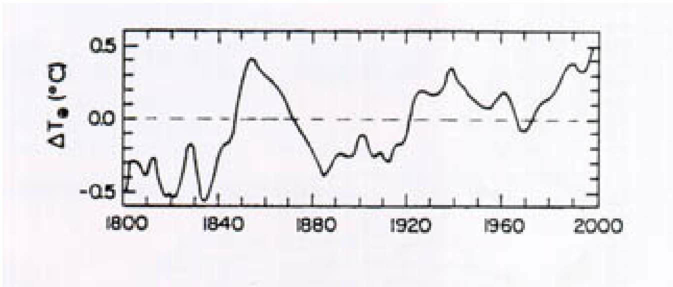


Figure 33: Northern Hemisphere temperatures modelled by Gilliland. Note the anomalously warm period coinciding with Palliser's exploration in 18571859.

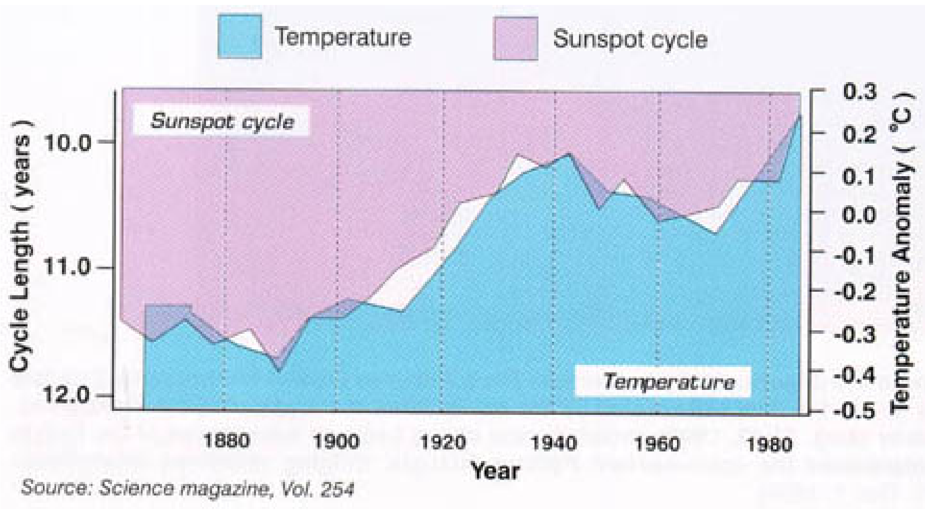


Figure 34: Smoothed sunspot cycle lengths and Northern Hemisphere mean temperatures. Although the 130-year temperature record shows warming, which could be partly caused by the increased greenhouse effect, the temperatures depart from the long-term trend from 1940. to 1970 and decreased in lock-step with a decrease in solar activity as indicated by the variation of the solar cycle length (Reproduced from THE GLOBE AND MAIL, June 3, 1995, p. D8).

Volcanic Dust Veils

The deceivingly wet period, 1911-1916 (Figure 6), which lured homesteaders into the Dry Belt, owed its existence to the four decade of anomalously cool temperatures from about 1875 to 1915 due primarily to decreased solar radiation. The first variation is due to the nadir in the 80 year solar luminosity cycle which Eddy denotes is called the "Gleissberg cycle". The second variation is due to the reduction in radiation reaching the earth's surface because of the dust veils created by two huge volcanic eruptions: Santa Maria (Guatemala) in 1902 and Mount Katmai's Novarupta (Alaska), in June 1912. The early 20th Century cooling may have triggered other favourable conditions, like countering the effects of the 1911-1912 El Nino.

The 0.7 degree cooling of the Northern Hemisphere, following the June 1991 mammoth eruption of Mount Pinatubo (Figure 35), verifies Gilliland's calculations of the temperature suppression by volcanic dust veils generated by extreme eruptions.

Nuclear and Dust-Storm Veils

Caution is necessary in assigning a cause to the cool period of 1953-54. Arakawa and Tsutsumisb, two Japanese climate experts, have attributed the cooling to the dust veil created by atmospheric nuclear tests. Hydrogen bomb tests had commenced in November, 1952 and continued into the spring of 1954. Since each explosion hurled an enormous volume of dust into the stratosphere, a dust veil was created resulting in temporary cooling of the Northern Hemisphere. Since the 1950's were an unusual period in Prairie agriculture, the literature on this topic should be compiled and studied.

The American solar scientist, I. F. Hand, was of the opinion that the cooling trend which brought an end to the Dust Bowl, was in part due to the dust lofted high into the atmosphere by the dust storms.

It is now evident that in the last two centuries, that variation in solar radiation has forced Northern Hemisphere temperatures to deviate by nearly 0.8 degrees Celcius from average. This fact has been largely overlooked by all the recent preoccupation with greenhouse gas warming.

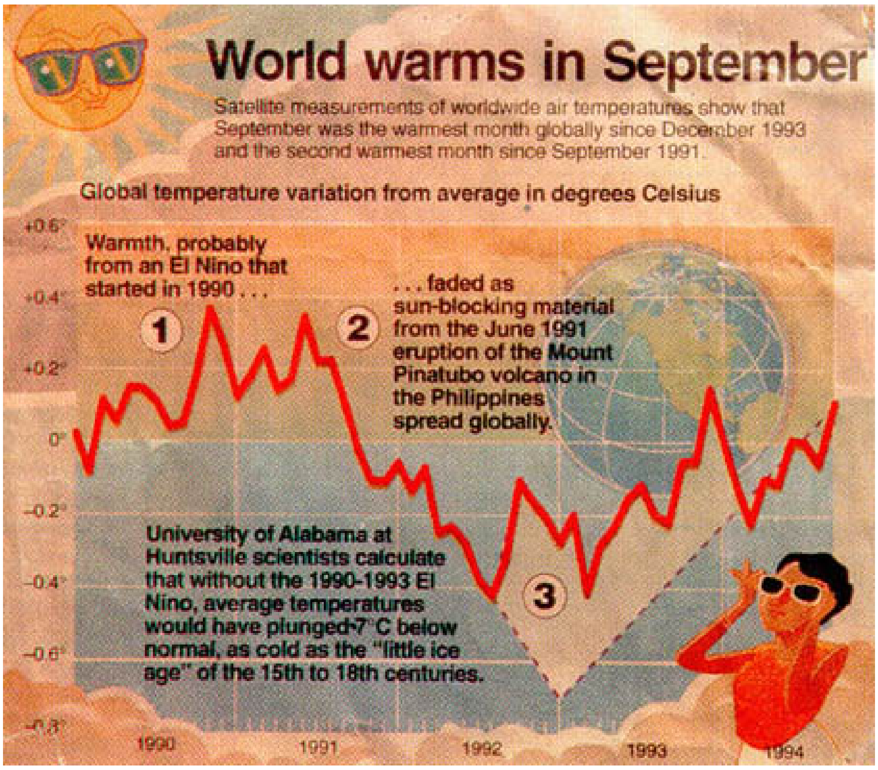


Figure 35: Recent global temperature departures from average. The 0.7 degree Celsius temperature drop late in 1991 and early in 1992, was due to the dust veil created by the Mount Pinatubo eruption in the Philippines. This cooling caused late summer (Aug. 21-23, 1992) snowfalls and killing frosts in many areas of the Prairie grainbelt. Heavy snowfalls blanketted the southwestern Palliser Triangle, lodging countless wheatfields. (Reproduced from, USA TODAY, Oct. 1, 1994).

Wheat Drought Areas in the Canadian Prairies

THE PRAIRIE GRAINBELT

The grain-growing regions of the Canadian Prairies, including the Palliser Triangle and the Peace River country, are outlined in Figure 36. Despite its northern location, vast tracks of fertile lands in the Peace River Country produce excellent harvests.

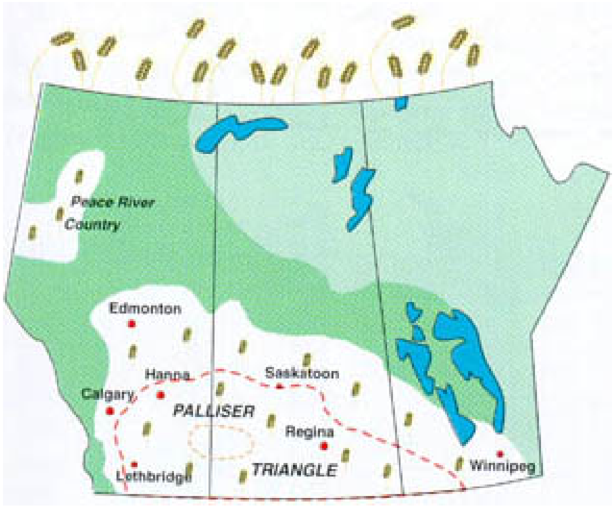


Figure 36: The Prairie grainbelt.

THE GRAINBELT CLIMATE

Longterm Average Precipitation

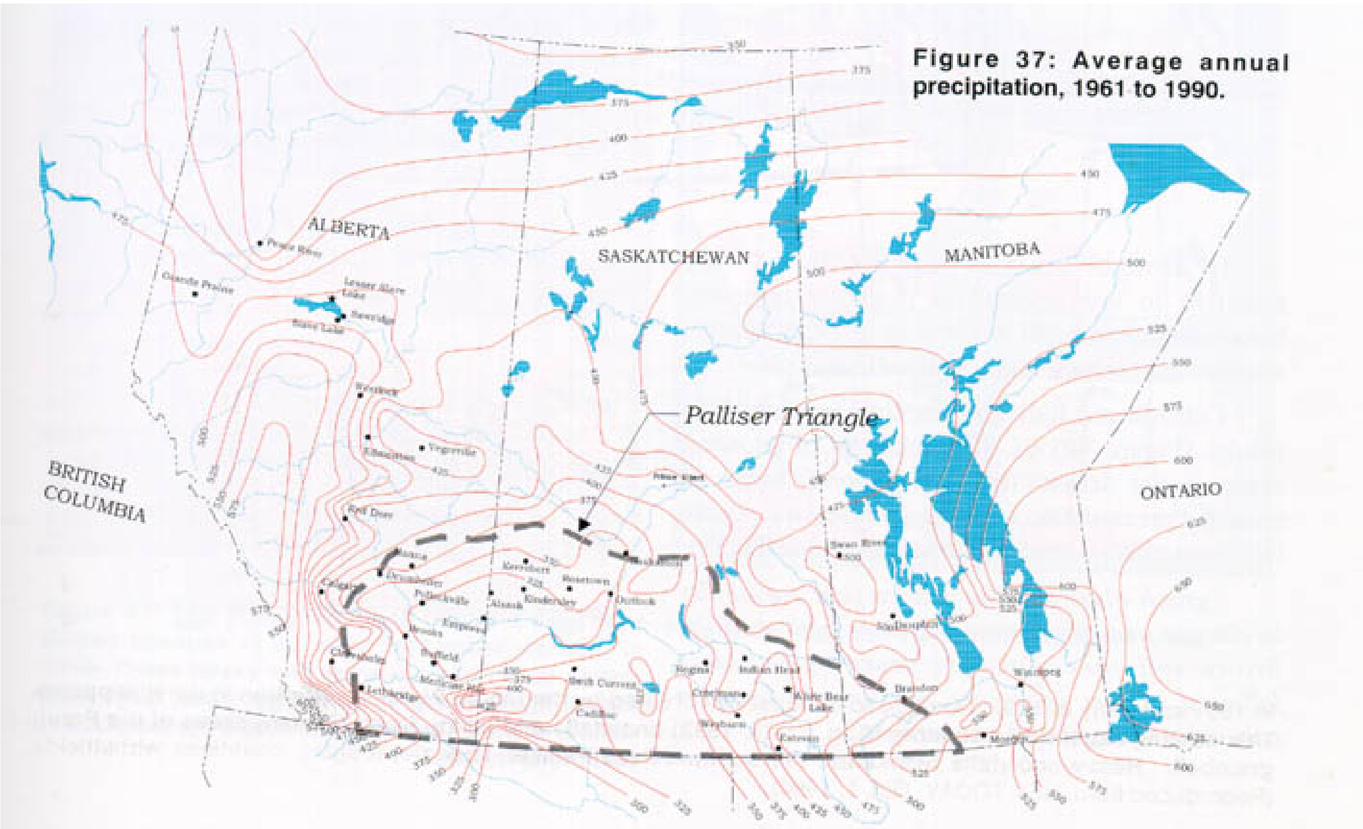
Climate is usually described by a series of longterm averages for precipitation (Figure 37), frost-free days (Figure 38) and temperature (Figure 39).

As a rule, 30-year averages are used to define various climatological parameters, such as the longterm annual precipitation. These averages can be misleading as they fail to provide a true picture of the vagaries in the Prairie climate. Nor do these averages accurately reveal just how vulnerable the Prairie grainbelt farming enterprises are to past, present and future climate extremes. This subject was explored by Hares' and others at a 1987 symposium on the impact of climate variability.

Precipitation During Extended Droughts

No single climatological parameter can adequately quantify either the severity or the areal extent of droughts. It is the conjugation of a number of unfavourable weather and agronomic conditions that create a wheat drought.

Figure 37: Average annual precipitation, 1961 to 1990.



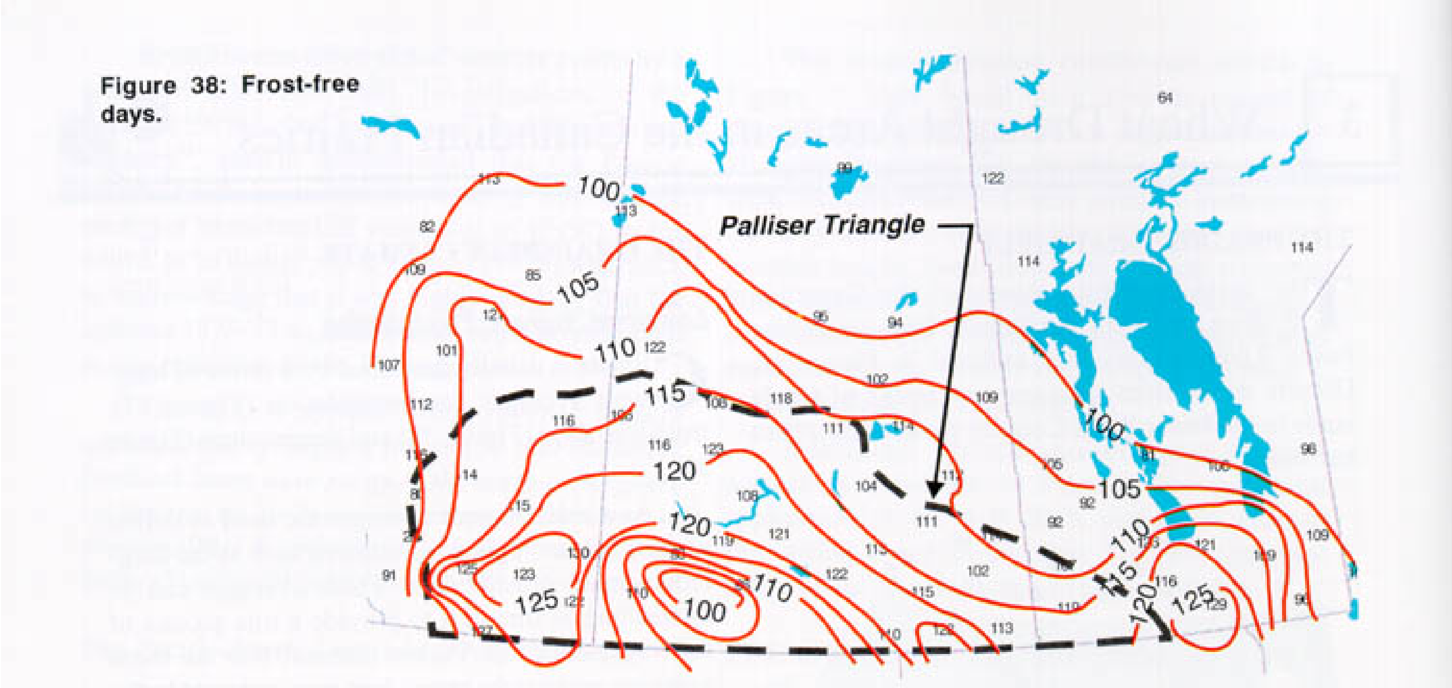
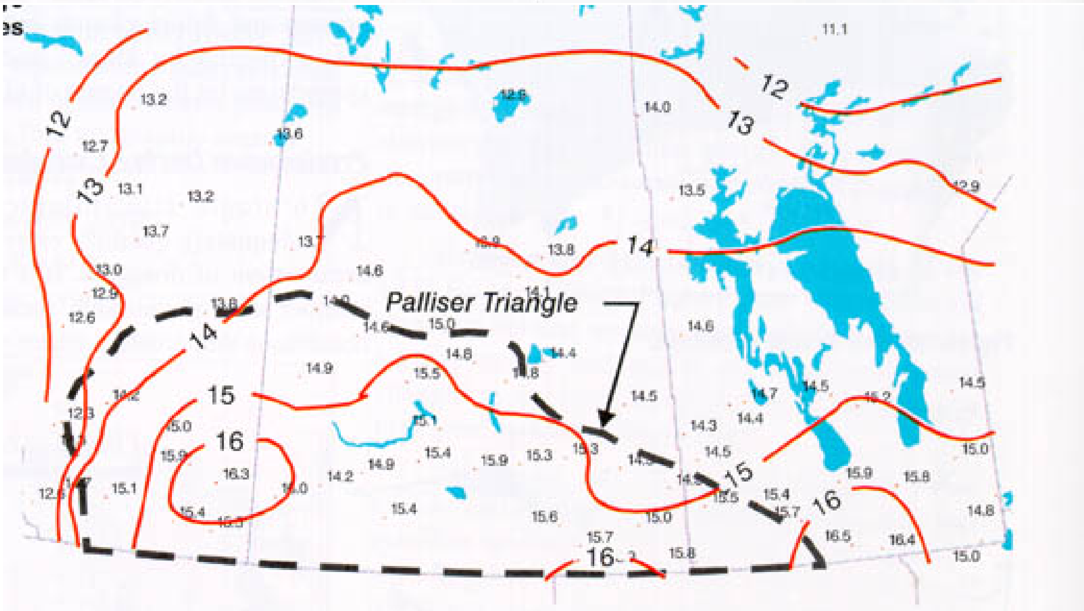


Figure 38: Frost-free days.



In drought years, wheat yields are very sensitive to low antecedent moisture reserves, below average rainfall in the crop growing season, summer heat waves, and hot dry winds.

Cutforth and Judiesch recently published the results (Figure 40) of their analysis of growing season water deficits (at Swift Current) based on recorded precipitation and temperature data. These two researchers were quick to acknowledge that the

"graph illustrates the year to year variability in climate and the climate extremes typical of the Brown soil zone. Drought years immediately followed by wet years are interspersed between periods of drought and wet periods ".

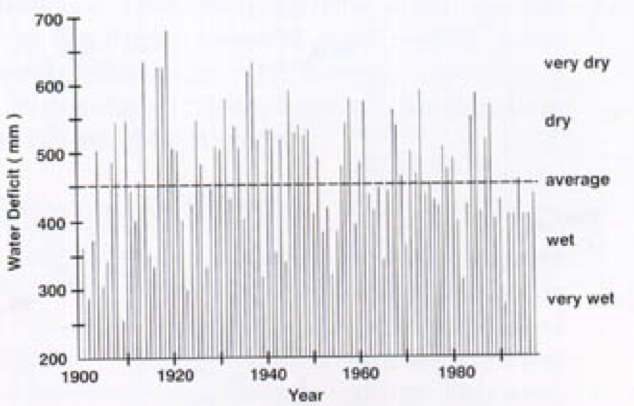


Figure 40: Growing season (May, June, July) water deficit, at Swift Current, estimated from temperature and precipitation.

The Swift Current research confirms the observations of various American experts. The USA Homestead Act of 1862 encouraged settlers to move into the Great Plains regions but few prospered. Rosenberg and Katz discuss the reasons for failure; the main culprit they said was the large fluctuation in rainfall between wet and dry spells.

To survive and prosper in a variable climate, Prairie farmers have had to adapt to a number of adverse conditions. In many crop growing seasons, agriculture in the northern fringes of the Prairie grain belt is vulnerable to late summer frosts, particularly in the Peace River Country. Droughts are rare but excessive early autumn rainfall can delay harvest. Early autumn snowfall can cause much damage by lodging standing wheat crops (Figure 41) throughout the grainbelt.

The unwelcomed September snowfalls are associated with "Colorado Lows" and appear to be related to the cold La Nina events. A cursory inspection of results compiled by Jones and Peterson, on precipitation during the two years after an El Nino, and the list of extreme La Nina events in Table 4, suggests that La Nina conditions may be responsible for the adverse Prairie harvest weather. It's an observation which merits further investigation.

HISTORIC WHEAT DROUGHT AREAS

Using a water budget approach to estimate wheat yields, Williams mapped the areal extent of 26 annual wheat droughts occurring from 1929 to 1980. Six of these drought areas, plus those of 1984 and 1985, are outlined in Figure 42.

Figure 41: Two combines stand idle in a field near Regina because of an early September snowfall in 1996. These heavy wet snowfalls can cause severe lodging of standing wheat crops throughout the Grainbelt (Regina LeaderPost photo).

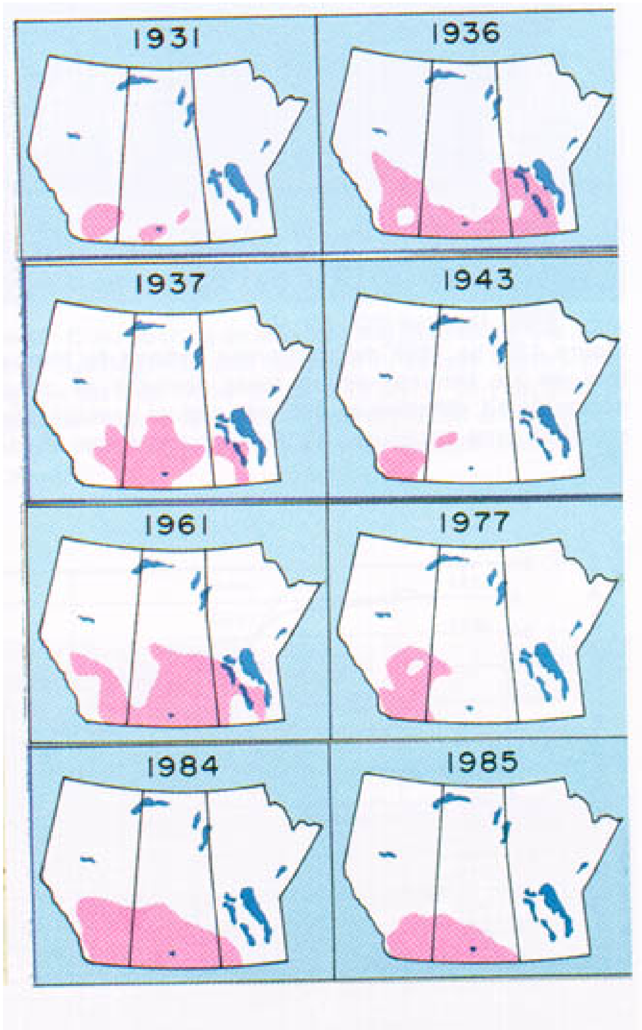


Figure 42: Historic Prairie wheat drought areas.

Williams found that the highest frequency of drought has been in the Dry Belt, followed by adjacent areas in the Triangle itself. The Peace River country has also experienced six droughts during the study period. A third distinctive drought area extends from east-central Alberta into northcentral Saskatchewan. Since the turn of century, 1988 appears to be the only year when much of the grain belt experienced severe drought (Figure 43).

Coping With Consecutive-Year Droughts

Modern farming technologies and practices now enable farmers to cope with single-year droughts. Most of the light lands in the droughtprone areas are now either community pastures or seeded to permanent cover. Yet even with modern technologies, the current wheatlands are not able to yield sufficient returns to justify cropping in the second drought year.

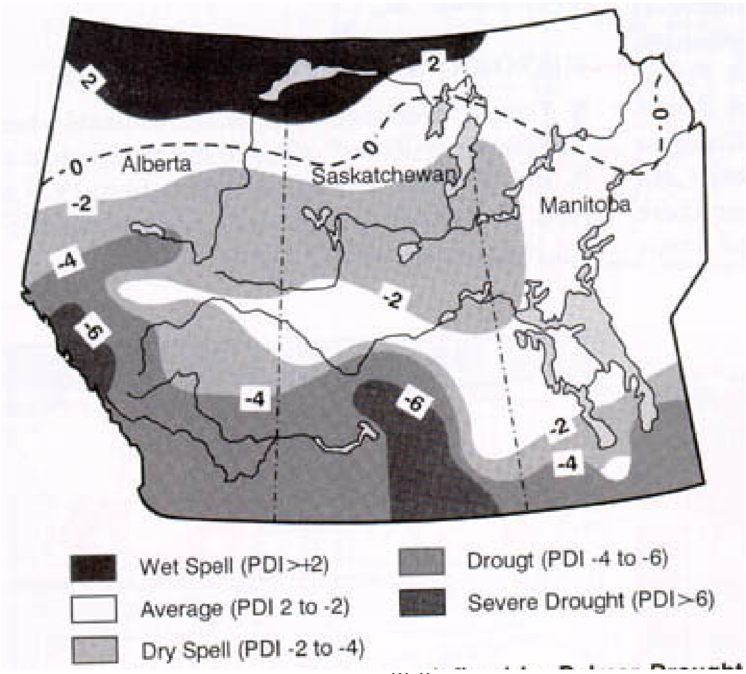
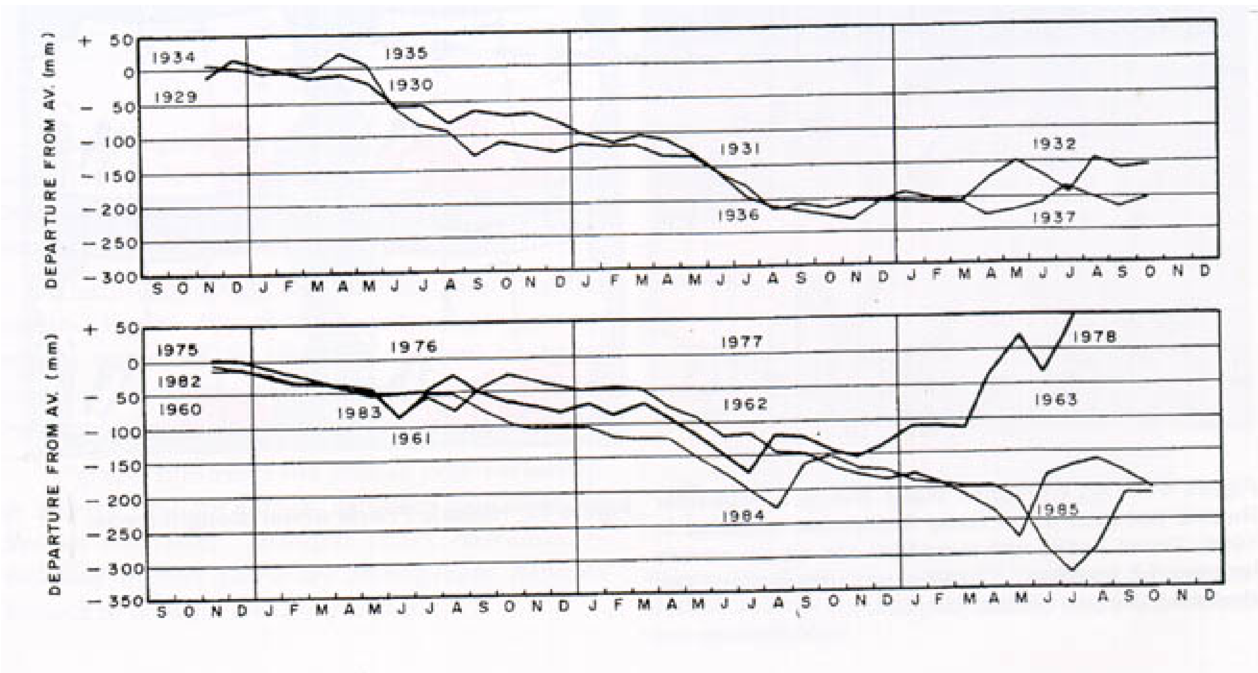


Figure 43: The 1988 drought areas defined by Palmer Drought Indices (in inches) which treat drought as a function of accumulated differences between actual precipitation and the required crop moisture. (Figure reproduced from Maybank, et al., 1995).

During the consecutive-year droughts, the precipitation deficit accumulates and leads to the depletion of the soil moisture in the root zone to a depth of a metre or more. During some extended droughts, the deficit accumulated at an annual rate of about 75 mm (Figure 44).

Throughout the Palliser Triangle, the impact of the accumulated deficit can bring the grainbelt to the verge of desertification, a process which actually occurred in the 1930's (see Figure 12 of a farm near Cadillac, Saskatchewan). There is no technology, apart from irrigation, which can sustain either cereal grain or hay production during extended drought periods in the Palliser Triangle.

Figure 44 (below): Accumulated precipitation deficit at Lethbridge during consecutive year droughts.



DROUGHT WEATHER PATTERNS

Spring and Summer Droughts

Studies of the Northern Hemisphere circulation, undertaken in the 1950's by the USA Weather Bureau under the direction of W. H. Klein", served to identify the principal storm tracks of migratory coldlows which were responsible for bringing precipitation into the Great Plains region. Klein's map of the June tracks is reproduced in Figure 45.

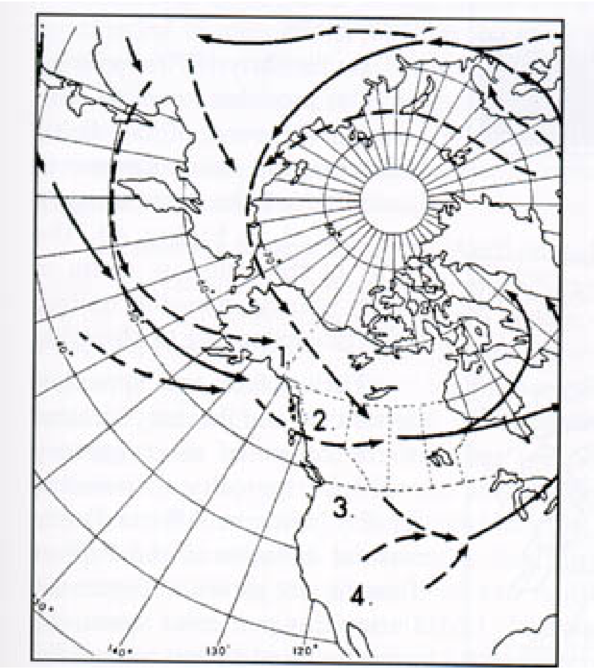


Figure 45: Principal and secondary tracks of migratory low pressure system for the month of June. The tracks are respectively: 1) Liard Gap, 2) Trans-Cordilleran, 3) Columbia River, and 4) Sonoran.

At about the time Klein was conducting his studies, world renowned meteorologist, Dr. Irving Krick, noted for his correct weather forecast for the historic D-Day invasion and for the cloud seeding experiments during the Alberta Hail Suppression study, identified 12 dominant, North American weather patterns. These formed the basis for his long-range weather forecasts".

Cognizant of Dr. Krick's work, Nemanishen and Meers, sought to identify the principal storm tracks responsible for the excessive spring and summer rainfalls in Northern Alberta. During their research, it quickly became obvious that extreme floods invariably coincided with droughts in the Northern Great Plains. This was quickly verified by comparing the historic flood levels of Lesser Slave Lake levels (Figure 46) with the USA Northern Great Plains', Palmer Drought Severity Indices (Figure 47) published by NATIONAL GEOGRAPHIC.

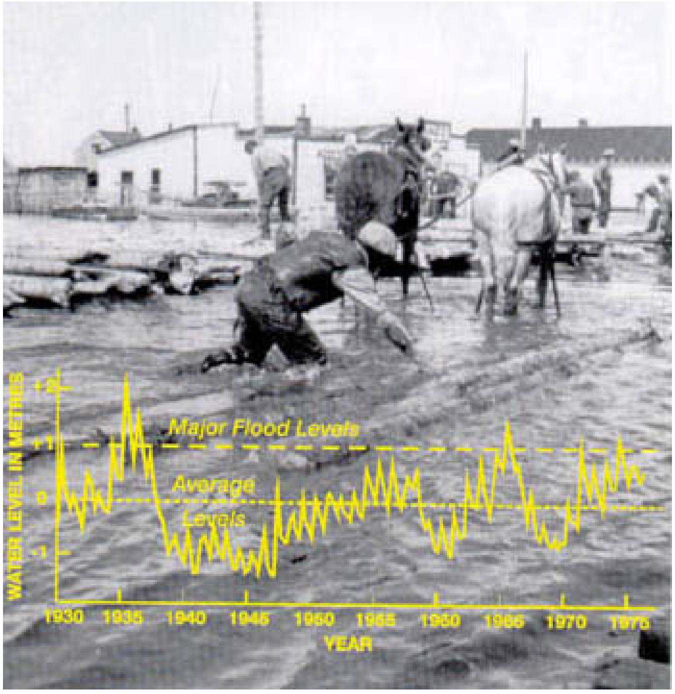


Figure 46: Constructing an elevated log road along the main street of Sawridge (a town adjacent to Lesser Slave Lake) during the historic flood of July, 1935). A 30-year plot of annual flood peaks is super-imposed on the scene (photo courtesy R.W.H. Eben-Ebenau: lake levels from Nemanishen and Cheng").

Figure 47: Northern Great Plains', Palmer Droughts Severity Indices super-imposed on a picture of a 1976, droughtravaged Minnesota field (National Geographic, V.150, #5, p. 598-599).

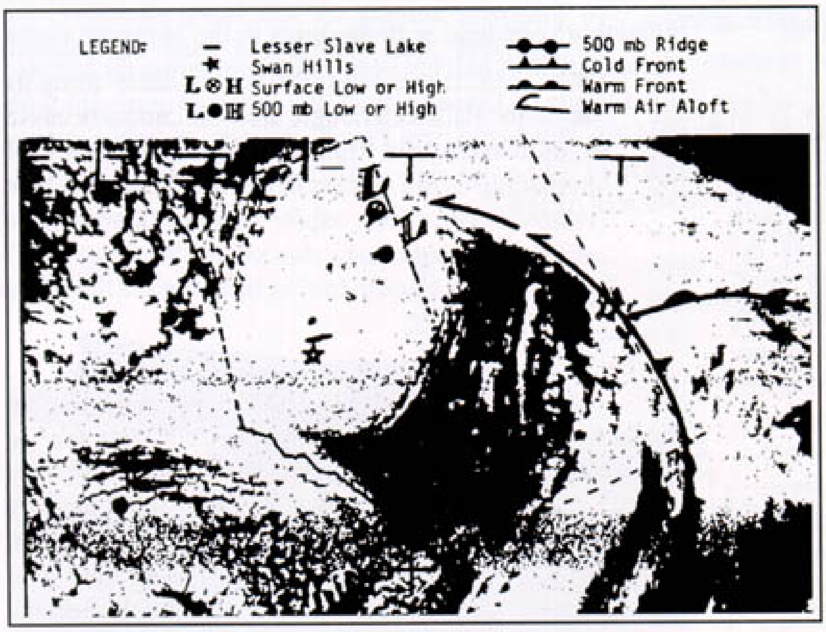


Figure 48: Satellite imagery, June 26, 1971
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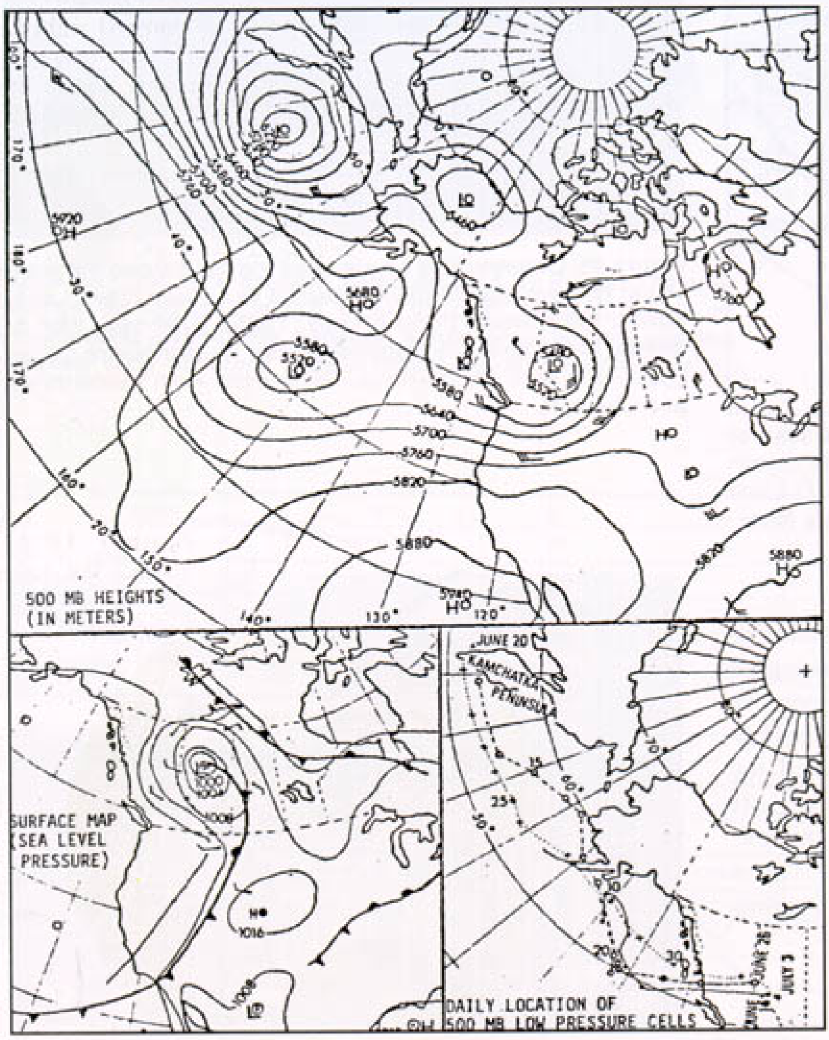


Figure 49: Surface and upper air weather maps, and storm track, for the June 14, 1971 storm which drenched Northern Alberta. Two more coldlow storms trekked along the same route to bring additional heavy rainfall on June 26 and July 3.

PFRA's ongoing drought studies were boosted when National Geographic lent support to these fledgling efforts by providing all the original notes and calculations of the scientists who had contributed to the Palmer Drought Severity Indices.

Some of the early droughtflood relationships were briefly described by Nemanishen in a paper prepared for the 3rd International Hydrology Symposium.

By the early 1970's, orbiting satellites provided scientists with a bird's-eye view of the Great Plains region, from Kansas to Lesser Slave Lake. In the imagery reproduced in Figure 48, the "eye" of the cold-low storm is clearly shown, plus the trailing cold-front extending to Montana.

The surface and upper air circulation, and the daily location of the centre of the migratory cold-low, typically responsible for the Northern Alberta floods and the droughts in the Palliser Triangle, are shown in Figure 49. During this particular storm, the closely spaced isobars around the "low" resulted in strong westerly winds in Southern Alberta and associated dust storms. Similar meteorological conditions in the 1930's created the violent, "Haboob" dust storms" (Figure 18) due to convective instability along the trailing cold front. Soil losses from summer-fallow fields were phenomenal because the surface was dust mulched in the mistaken believe that this would conserve soil moisture by preventing upward migration by capillary action.

The Summer Drought of 1988

In the section on Historic Wheat Drought Areas, Ithe extreme drought of 1988 was highlighted. Trenberth, Branstator and Arkin explored at length the multiple causes of the 1988 drought and concluded:

" Along the West Coast and in northwestern United States drought conditions developed during 1987 in association with the 1986 to 1987 El Nino conditions in the tropical Pacific Ocean. Record low rainfalls from April to June 1988, led to rapid development of the drought in the North Central United States. Strong anticyclonic conditions and a northward displaced jet stream in the upper atmosphere over North America throughout this period were but a part of a pronounced and distinctive wavetrain of anomalies in the atmospheric circulation that appeared to emanate from the tropical Pacific. "

Trenberth's illustration of the April-May-June 1988 wavetrain of anomalies is reproduced in Figure 50. This wavetrain displays the classic 4-Pt PNA Pattern described in Part 2 and shown in Figure 27. The three authors provide further insight into the persistence of drought: "In general in summer, once anticyclonic conditions (eg., high pressure systems) prevail over the United States, other local factors probably help maintain droughts and produce heat waves. In particular, land-surface processes involving the absence of soil moisture probably have a significant effect. Normally, heating from the sun is partitioned into evaporation and sensible heating of the surface and the atmosphere. But in drought conditions, evaporation and plant transpiration are greatly reduced so that nearly all heating is manifested as temperature increases. Moreover, the absence of moisture conspires against widespread precipitation. Heat waves result and a drought becomes in part, self-perpetuating."

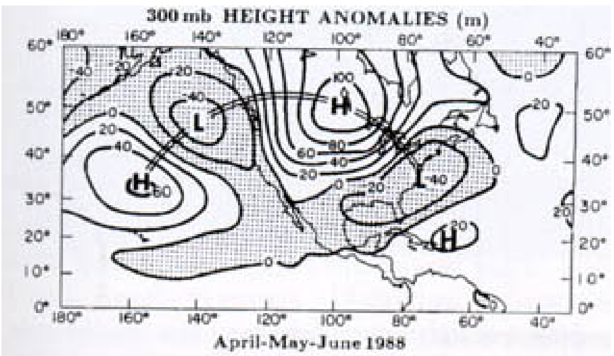


Figure 50: Classic 4-Pt PNA Pattern based on 300 mb height anomalies during the April-May-June 1988 drought (Trenberth's et al's., Fig. 5).

<u>*Fall and Winter Droughts*</u>

The physical causes of fall and winter droughts in the Palliser Triangle are well known because of numerous investigations into the causes of anomalously cold winters in Central Canada and the American east coast and the midwest, particularly the winter of 1976-1977.

The Winter of 1976-1977

Many reports have been published on the bonechilling 1976-1977 winter in the eastern American states and in central Canada. In a feature story, National Geographic, heralded it as "The Year the Weather Went Wild." The lengthy scientific article contrasted the cold, wet eastern weather with the drought conditions in the Great Plains and the western coast. The article became another corner stone in PFRA's drought investigations as it focused attention on the interaction of six critical oceanographic - atmospheric processes, illustrated in Figures 51 and 52:

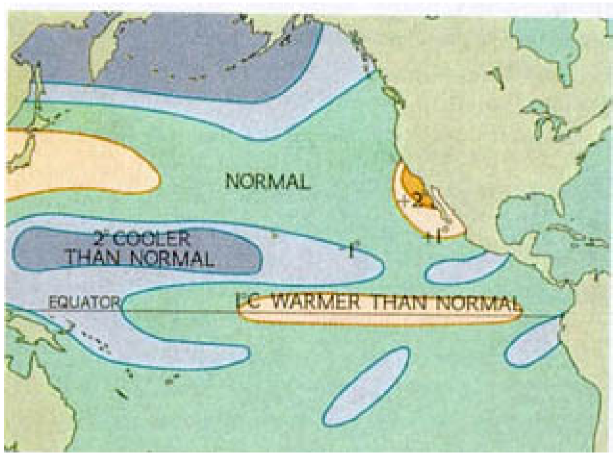


Figure 51: Pacific SSTs, November 1976. (Reproduced from NATIONAL GEOGRAPHIC, **Vol. 152,**

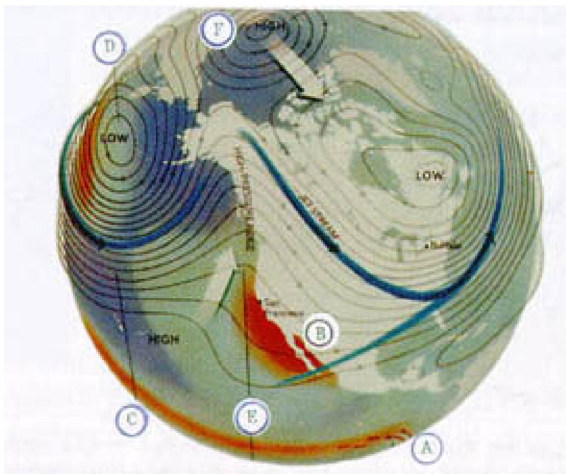


Figure 52: North America weather circulation during January, 1977. (National **Geographic, Vol. 152, No. 6).**

A: El Nino conditions along the coast of Peru;
B: accumulation of warm water along the western coast of North America (a derivative of El Nina);
C: cool Pacific-North American (PNA) ocean temperatures;
D: formation of a massive low-pressure system (the so called, "Aleutian Gyre') that expanded to fill the entire North Pacific;
E: northward displacement of the winter high pressure system which in turn displaced the polar low-pressure centre southeastward over Canada; and
F.- quasi-stationary high pressure ridge along the western coast which caused the jet stream, which had looped-around the Aleutian Gyre, to deflect into the High Arctic, become super cold, turn southeastward and bear-down on Central Canada and American east coast. "And the disaster was born. "

Within a year of the National Geographic feature story, other scientific articles appeared, notably, Dr. Jerome Namias', "Multiple Causes of the North American Abnormal Winter 1976-77. He concluded:

"The autumn pattern of southerly airflow over the eastern North Pacific reduced heat losses from the ocean, induced advection of warmer waters, and reduced coastal upwelling. Meanwhile, the cold sea surface temperatures generated in spring and summer over the central North Pacific persisted. These cold waters seem to have been generated by the persistently strong Aleutian low which, following Bjerknes' hypothesis, was associated with a persistent El Nino which began several months before and lasted through the abnormal winter . ... The "signals" of the oncoming winter's patterns were clear by November to permit a reasonably successful long-range forecast. "

The Aberant Winter Drought of 1961

Attempts at correlating Palliser Triangle droughts directly with ENSO events are frustrated by certain severe but aberrant drought years, like 1961. This particular drought year, ranking with the six worst in the 20th Century, actually coincided with the La Nina phase. This fact has lead some to incorrectly conclude that it is the cold ENSO phase which causes Palliser Triangle droughts. In reality, the 1961 drought was probably related to the strong, 1957-58 ENSO (Figure 24). Since there are a number of important lessons to be learnt from the 1961 drought, a discussion of its probable causes is deferred to Part 4.

The Winter of 1987-1988

When El Nino conditions developed late in 1986 and persisted throughout the summer and fall of 1987 (Figure 24), it was evident from Dr. Namias' model that severe drought could be expected in the Palliser Triangle in 1988. Trenberth et al., have identified some of the fall precursor signals (Figure 53) to summer drought in 1988, a number of which had already been described by Canby, Namias and others:

A: anomalous El Nino SST's along the eastern equatorial Pacific;
B: large displacement of the major rain producing convergence zones in the tropics;
C: stronger than average ridge of high pressure in the vicinity of the west coast of the USA;
D: lower than average pressure in the North Central Pacific Ocean in the Aleutian Gyre as part of a train of waves emanating from the equatorial Pacific Ocean, referred to as teleconnections.

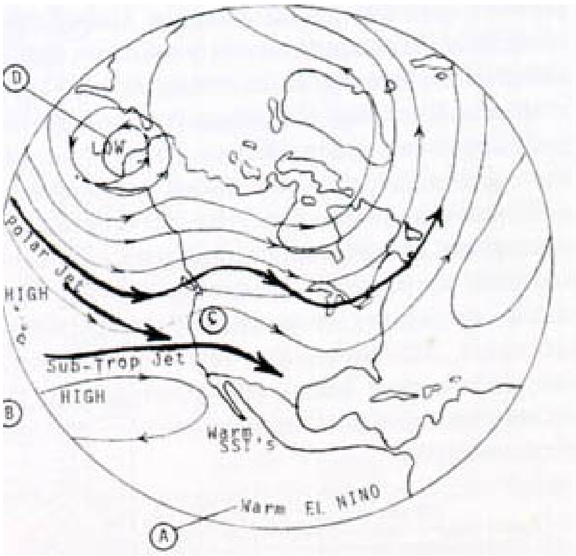


Figure 53: The 1987-fall precursor signals to drought.

Wagner" commented on a weak but persistent trough just off the coast of California:

"Even though this trough was weaker than normal, a noticeably stronger-than-normal subtropical ridge extending from Baja, California westward to Hawaii contributed to enhanced 700mb westerlies north of the trough that fed Pacific moisture, some of it the remains of tropical storms,

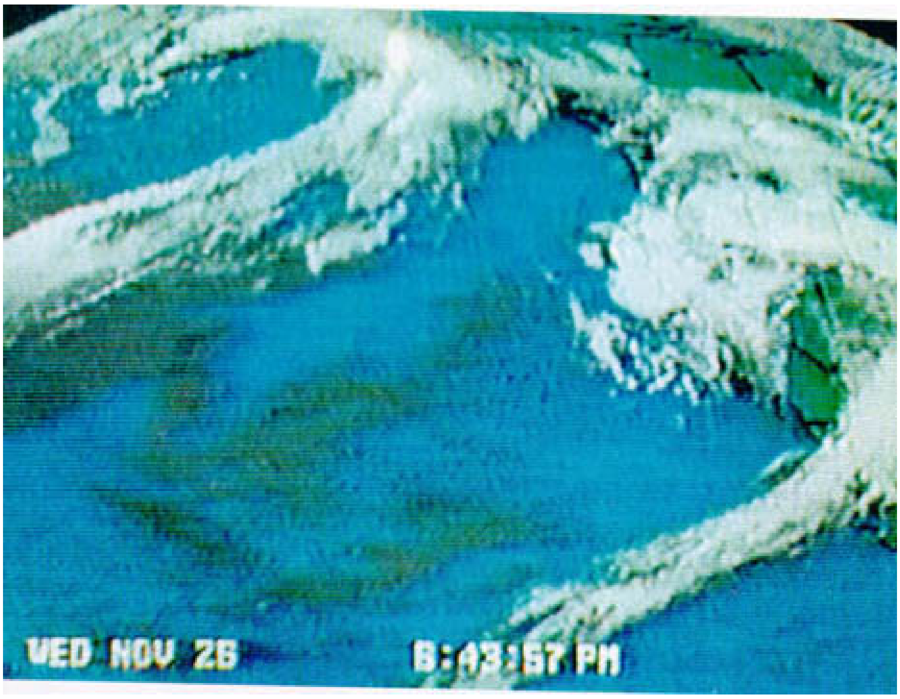


Figure 54a: A November 26, 1997, weather satellite image captures twin, cold-low pressure systems over Northwestern America. Each system is steered by a strong jet stream. Coastal California was deluged by rainfall while snow fell over the Sierra Nevada Mountains. Parts of Colorado were blanketed by a metre of snow. Due to the influence of Aleutian Gyre (Figure 54b), the northern system proceeded up the coast after reaching British Columbia.

into southern California and the lower Great Basin. Evidence of wind currents steering the moisture shows even more strongly at higher levels, where a rather persistent subtropical jet stream was in evidence most of the time between Hawaii and southern California. "

American meteorologist, Gail Martell, stressed the importance to southern Alberta of the split jet stream in explaining the cause of the dry 1987-88 winter:

"The strong branch is the southern (subtropical) jet which steers one storm after another into the California coast. The weak sister is the northern (polar) jet stream, which tends to swing northward through the Gulf of Alaska and northern British Columbia. In between the two storm tracks, the Prairie Provinces are left high and dry. "

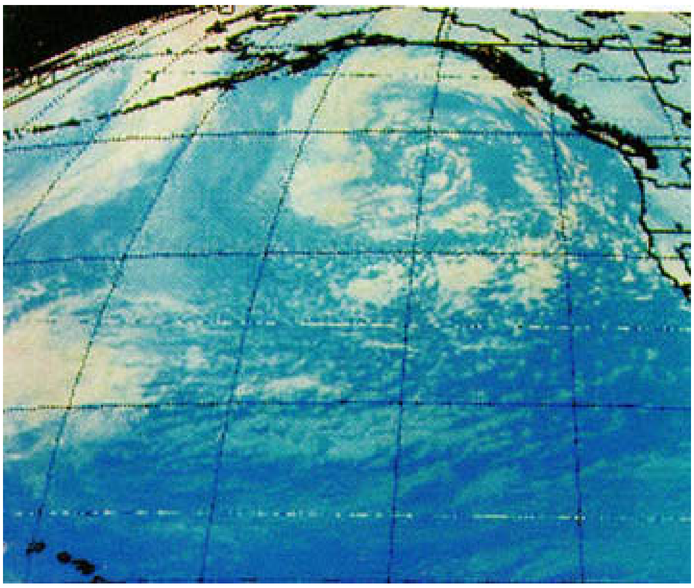


Figure 54b: November 14, 1997, GOES-9 satellite imagery of Pacific northeast and Western North America. The Aleutian Gyre is outlined by the counter-clockwise rotating clouds. In time-lapse photos, the motion of the Gyre is very evident.

Fall 1997

Fall weather conditions in 1997 have been reminiscent of 1987. Although it has been essentially warm and dry in the Palliser Triangle, the western coast lines of the USA and British Columbia have been subjected to series of high wind storms, torrential rainfall and even heavy snowfalls in the interior mountain ranges of Northern California and Colorado. As though one huge storm event was not enough, the November 26, 1997 satellite imagery (Figure 54a) captures twin, low-pressure systems simultaneously battering the USA and the Canadian western coastal regions. Weather forecasters usually nickname the USA storms, "The Pine-Apple Express" since they are spawned by the warm ocean waters around Hawaii.

SUMMARIZING THE DROUGHT LESSONS LEARNED FROM EVENTS SINCE 1976

<u>Palliser Triangle Droughts are Linked to ENSO</u>

The scientific evidence presented in this part proves conclusively that Palliser Triangle droughts are linked to the eastern-equatorial Pacific ENSO events. The linkage is through a series of interlocking derivatives of warm El Nino SST's and the Southern Oscillation. There are a number of unknowns in this ocean-atmosphere process. In Part 4, some of these will be addressed.

<u>A Positive. 4-Point PNA Pattern Brings Drought</u>

A few months after the onset of an ENSO, a series of anomalous circulation patterns are established over the Pacific-North American (PNA) ocean region and over the North American continent. The dominant features of the fall circulation are shown in Figure 55. This is the positive PNA Pattern, comprising a quasi-stationary low in the Gulf of Alaska, a blocking high over northwest and a low over the USA south east. Weather expert, Mary Murray advises that this is a relatively stable and persistent weather pattern.

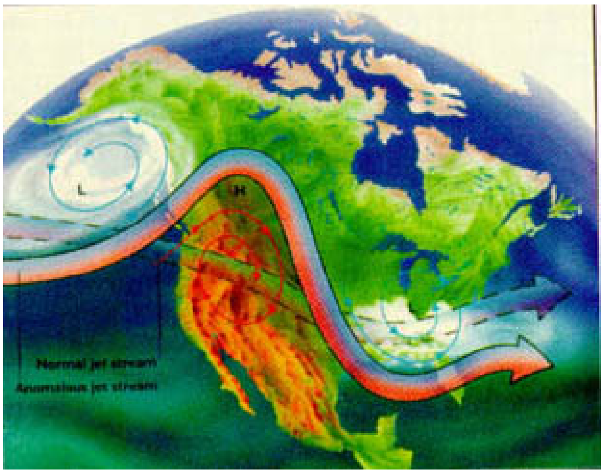


Figure 55: The Positive PNA Pattern which is the primary cause of Palliser Triangle droughts, comprises the huge Aleutian Gyre of low pressure (L), the Alberta high-pressure ridge (H) and the lowpressure system (L) over the USA southeast. (Reproduced from Murray).

Portions of the positive 4-Pt PNA Pattern are shown daily on TV weather reports (Figure 56). Last fall, the positive PNA Pattern favoured the Prairies with warm dry weather while eastern Canada and the American northeast had to contend with snow.

Figure 56: Meteorologist, Michelle Skinner, highlights the jet stream location, weather systems and temperatures on the first full autumn day, September 23, 1997-Indian-Summer in the West but blustery conditions in Central Canada.

<u>Droughts Are Not Random Events</u>

American drought expert, Prof. L.M. Thompson, was one of the earliest weather researchers to challenge the assumption that droughts were random events. The present level of scientific knowledge tends to support Prof. Thompson's reasoning. We now know that major droughts are linked to ENSO. Since ENSO events occur frequently and are now predictable, they cannot be considered random-nor can droughts. There is an important lesson to be learnt. Those who would still cling to the unproven assumption that droughts are random occurrences should heed Rudyard Kipling's admonition to another professional group who had trouble learning from frequent painful experiences. Kipling was perceptive on this point:

Let us admit it freely as a business people should,
We have had no end of a lesson, it will do us no end of good.

Lessons from historical El Niños and Droughts

In this part of the Primer, the role of the North Pacific Ocean temperatures is examined. The present level of scientific knowledge of the drought drivers is then used to pan through historic reports for some evidence that the Northern Great Plains' droughts prior to 1976 were related to ENSO events.

PACIFIC-NORTH AMERICAN OCEAN SST'S
The two preceding parts attempted to unravel the complex interplay of El Nino, the Southern Oscillation, and the Pacific-North American weather pattern, in creating Palliser Triangle droughts. Easily overlooked however, is the role of the Pacific-North American SST's. The ocean temperatures adjacent to the North-American west coast (NAWC) appear to be one of the key factors in Palliser Triangle droughts. This part of the ocean is probably the heat sink which powers the Aleutian Gyre. Namias investigated the links between periodic climatic variations over North America and the Aleutian low and its upper-level wind patterns.

Origin of the Warm Ocean Ad iacent to the NAWC
Recently, there have been a series of hasty attempts to correlate various Palliser Triangle agronomic and climatological factors directly with ENSO related parameters. Some dismal failures have ensued. It is necessary to use a "derivative" of ENSO. The term implies that the parameter derives from the ENSO phenomena. Khandekar has applied this term to the monsoon predictors (discovered by Walker) which are directly or indirectly related to the Southern Oscillation (SO).

It is not completely clear from the published literature exactly how the anomalously warm waters reach California and further north. A clue might be found in Ramage's article, El Nino. Figure 57 reproduces an illustration by Ramage which represents the difference in SST's between August 1972 and August 1979, respectively El Nino and La Nina years.

There is a strong hint in Ramage's map that the warm waters pooled adjacent to the Baja Peninsula derived from El Nino Region 4. Lending credence to this speculative idea is the undeniable evidence of such a warm-current trajectory in the September 3, 1997, satellite image in Figure 21.

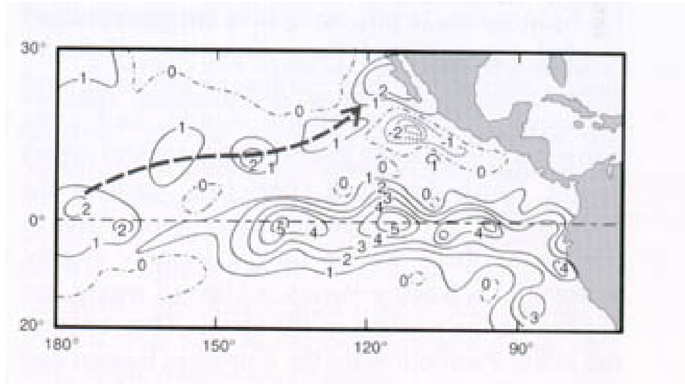


Figure 57: Differences in SST's between the August, 1972 El Nino and the August, 1979 La Nina; trail of warm SST's outlined by the arrow (from Ramage).

The oceanographic and atmospheric processes by which the vast pool of warm El Nino waters, accumulated in the Indonesian region of the Western Pacific, reach the equatorial coast of South America are well known. These are illustrated in Figure 58.

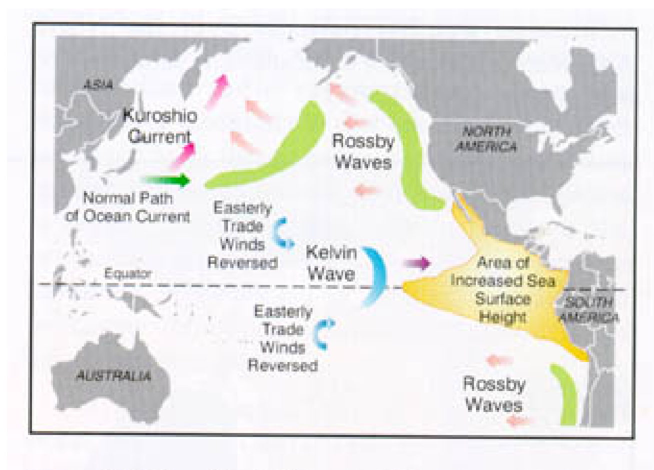


Figure 58: Simplified diagram of the atmospheric and oceanographic currents creating the "derivative" warm pools of water of the USA and Canadian coast line. (The source of this illustration is not known).

At the onset of the SO, the easterly Trade Winds weaken. If the ENSO is very strong, like in 1997, the Trade Wind reverse (as shown in Figure 58) and blow from the west. While Trade Winds had been blowing from the east, warm water had been piled-up in the Western Pacific and attained a higher elevation than the east-coast ocean surface. Once the easterly winds diminish or reverse, gravitational forces start to transport the warm pool eastward in a series of huge waves, known as Kelvin Waves. Each successive wave takes one to two months to traverse the equatorial Pacific. Their eastward movement is facilitated if the Trade Winds reverse and cause the EL Nino waters to pile-up against the west coast of Central America and Peru. Gravitational forces again contribute to their northward and southward dispersal. Strong cyclonic winds, and even hurricane winds, assist in dragging the warm waters up the North American coast line, creating the "derivatives" pools of anomalously warm water. A portion of these waters flow extremely slowly, westward, as Rossby Waves, a class of waves that depend on the rotation of the earth. They traverse the North Pacific toward the Kuroshio Region east of the Philippines and Japan, by a process described by McPhaden. These waves deflect the strong, warm Kuroshio Current northeastward into the North Pacific Aleutian Gyre region, producing unusually warm sea surface temperatures across the Pacific from Japan to North America.

The 1961 Drought: An offspring of the 1957-58 ENSO?

Studies by Jacobs, et al., conclude that the complex, 1982-1983 El Nino derivatives-the ocean currents and Rossby Waves-may have influenced weather patterns over the North American continent for a decade. The same may be true of other strong ENSO's.

The Palliser Triangle drought of 1961 may owe its origin to the 1957-58 EN SO. This severe drought occurred when no ENSO conditions existed but warm SST's persisted until 1959 at the Peruvian coastal village of Chimbote. During the winter of 1960-61, a pool of anomalously-warm coastal waters extended from the Baja Peninsula to Vancouver Island. Furthermore, a 4-Pt PNA Pattern existed (Figure 59). The SST's in the Kuroshio region of the Western Pacific may also have had a role.

The Kuroshio Teleconnection

Relter and Chen have investigated the Kuroshio Current and have established a teleconnection between SST's in the Kuroshio Region and the late-winter temperatures over the eastern United States. This teleconnection may explain why there is some evidence that Great Plains' droughts appear to originate in the south and migrate north as described in the next section.

THE CREEPING DROUGHT PHENOMENON

Although not extensively investigated, Hoffman recently suggested that the 1930's droughts first began in Texas and Oklahoma and swept northward. Some preliminary studies at Iowa State University by Dr. Louis Thompson [8] tend to support the theory of drought migration. This subject merits further attention.

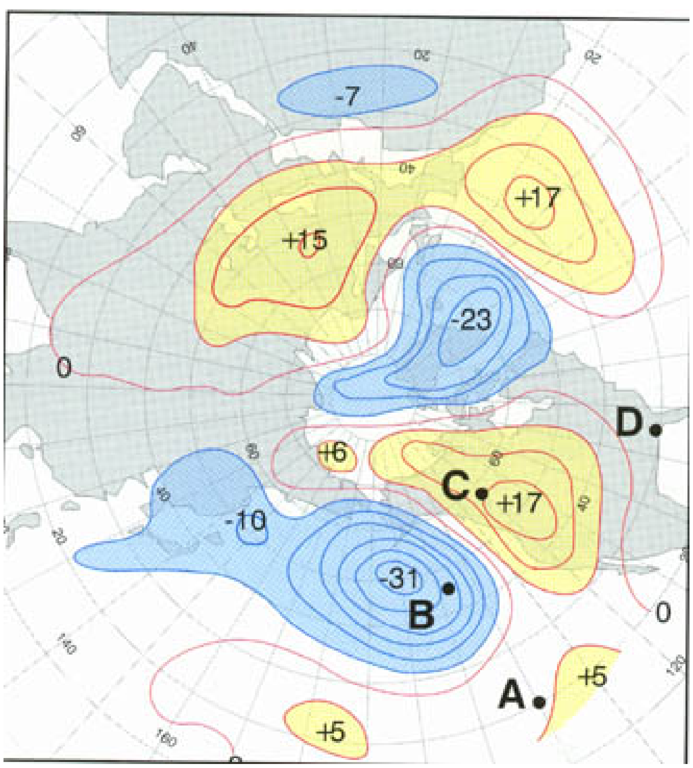
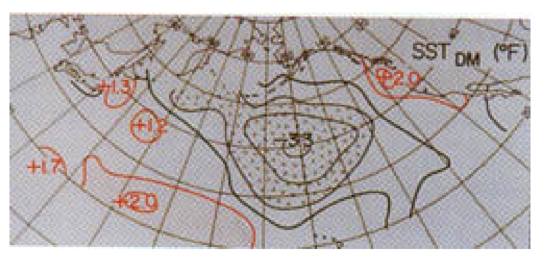


Figure 59: (left) The 700-mb height anomalies (in tens of feet) for the winter of 1961. The positive 4-Pt PNA Pattern for this winter, which was a precursor to the severe drought of 1961, is evident. (below) The North-Pacific SST anomalies for the corresponding period are shown on the small map below. (Reproduced from the **CALIFORNIA COOPERATIVE OCEANIC FISHERIES INVESTIGATIONS, ATLAS No. 27, June 1979).**



EVIDENCE OF HISTORICAL, ENSO "DERIVATIVE" DROUGHTS

Captain Palliser's report to the British Parliament, on his three years of exploration of western Canada, contains sufficient evidence to conclude that his sojourn coincided with an ENSO derivative drought.

The following evidence is congruent with recent observations:

- The ice on Lake Superior did not thaw until mid-June, 1857. Captain Palliser chartered a steamer to cross rather than following the example of the Governor of the Hudson Bay Company who resorted to large canoes-some of which were wrecked by pack ice. He writes": *"Owing to the unusual lateness of 'the season, Lake Superior was crowded with floating ice, offering great difficulty even to the steamer, ... qfter consulting with experienced persons, I determined to accept the further assistance of the steamer, "Illinois ", whose captain agreed, for the sum of $300, to take my canoes on deck, 16 voyageurs, and ourselves across the lake, and leave us near Isle Royale, about eight hours' paddling distance from Fort William. ...- We came on fields office, and the captain, qfter pushing his way for several miles, fell in with a schooner that warned him to return and try a course along the north shore of the lake. We arrived at Fort William on the 12th of June ... we learned that Sir George Simpson had only, proceeded us by 11 days, having been eight days on the north shore of Lake Superior where his canoe had been broken on the ice. "*
- Mid-winter conditions in central Alberta were so warm and snow cover so scant, that Palliser and his explorers had great difficulty in finding enough snow covered ground to dog-sled from Fort Edmonton to Rocky Mountain House.
- Warm chinook conditions greeted Palliser at his destination.
- The following summer, Palliser found that many shallow Prairie lakes were dry.

Based on the above, and the explorer's graphic description of Sullivan Lake, Nemanishen and Woodvine have concluded that Captain Palliser's drought probably ranks in severity with the 1984-1985 ENSO derivative droughts.

2. In the Dirty 1930's Droughts

Hoyt's Report on the USA Great Plains' Droughts

The devastations caused by the 1930-1934 drought period in the USA Great Plains region are documented by Hoyt. He cited three primary causes of the droughts: deficient and unfavourably distributed precipitation, excessive heat, and warm winds. Almost as an after-thought, Hoyt made a sweeping statement that these conditions prevailed *"in all States except those bordering on the Atlantic seaboard, eastern Gulf of Mexico and northern Pacific coast."* His comments on the USA temperature regime are equally as important to us now in fingering the exact cause of the 1930's Great Plains' droughts:

"During 1934, especially in the first 8 months, unusual temperatures were noticeable in most sections of the country. The winter in the Northeastern States was much colder than usual, and in February most previous records as to both severity and duration were broken in this area as far south as Virginia. On the other hand, States west of the Mississippi had a mild winter. The spring, in general, was late in the Northeastern States and early in the Northwestern States. "

Hoyt's observations mirror the conditions which prevailed during 1976 to 1977 drought years, and also during 1983-1984. Autumn and winter circulation would have been similar to that shown in Figure 55.

The Palliser Triangle Evidence

Drought was still a poorly understood subject when the Saskatchewan Drought Commission was established in 1931. Since farmers have always been keen observers of weather, they were quick to offer ideas to induce moisture-laden clouds to surrender their rain. Given the mysterious aura surrounding radio signal transmission and atmospheric electricity in that era, the Commission was urged to try these new mysterious forces. Some farmers advocated the use of radioactive radiation to reduce the dry air insulation between the overhead, rain-swollen clouds and the parched farmlands. Some argued for the need to understand the connection between electrostatic conditions of the air and drought.

Although James Gray, in his monumental work, MEN AGAINST THE DESERT, deals at length with many aspects of the 1930's droughts, he is strangely silent on their origins. Moose Jaw district farmer, Leslie Ashton, offers several critical observations:

"The 1928 crop was a bumper one in Western Canada and the fall was dry and clear throughout; the last rain (of a general type) ,fell on July 6, or possibly July 29, and no appreciable rain of either type was received for several years, ... on the writer's farm only one and one-half inches of snow fell that winter . ... What rain clouds do come around simply pass over to some place where a sufficient

supply of moisture remains to trigger the necessary primary precipitation ... when the rains that were lost to the Prairies had to travel clear across to the Great Lakes district, gathering moisture all the way, until they encountered air damp enough to trigger them off, and they then just about drowned out everything there, and thoroughly ruined the Niagara, fruit crops with rains that should have been ,first deposited on the prairie wheat fields. "

Without even having to embark upon lengthy climatological search, it is evident that this farmer's keen observations point an accusing finger at anomalously warm sea-surface temperatures as the basic cause of the Dirty Thirties' drought. Yet the primary cause of these SST's may not have been exclusively due to ENSO conditions. The subject needs careful investigation in the author's opinion. The anomalously high Northern Hemisphere temperatures (Figure 60) probably sustained the warm SST's in the Aleutian Gyre responsible for deflecting the Pacific cold-lows across Northern Alberta.

The 1930's were a period of extremely high solar radiation (Figure 61). During this decade, in nine of ten years, the solar radiation was above average. This was likely one of the primary causes of the global warm period which continued until 1950 (Figure 60). Between 1920 and 1945, major volcanic activity virtually ceased (Figure 62); consequently, the atmosphere was very transparent. The repeat of similar conditions in the late 1980's motivated University of Chicago Professor, Dr. Paul Handler, in 1989, to hope for a major volcanic eruption to cool the Northern Hemisphere. Dr. Handler, who had two years earlier correctly predicted the 1988 drought, expressed his views in a speech to the Chicago Farmers' Club". His 1988 drought prediction had been made partly on the bases of an exceptionally clear stratosphere. Dr. Handler had only to wait 17 months. Mount Pinatubo answered his hopes in June 1991.

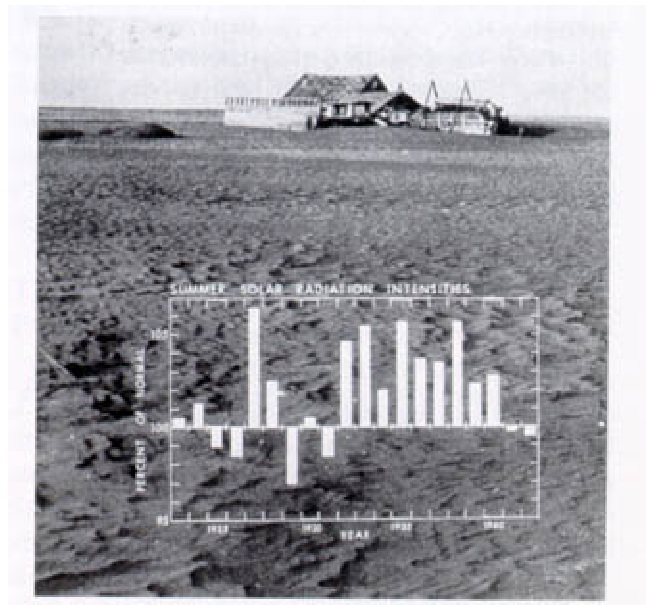


Figure 61: High solar radiation intensities sustained the Dirty Thirties drought and dust bowl era. Is this the "smoking gun" evidence linking excessive solar radiation to prolonged drought? (PFRA photo 25960, c. 1936, of a drought-stricken farm in the Cadillac district of southwest Saskatchewan).

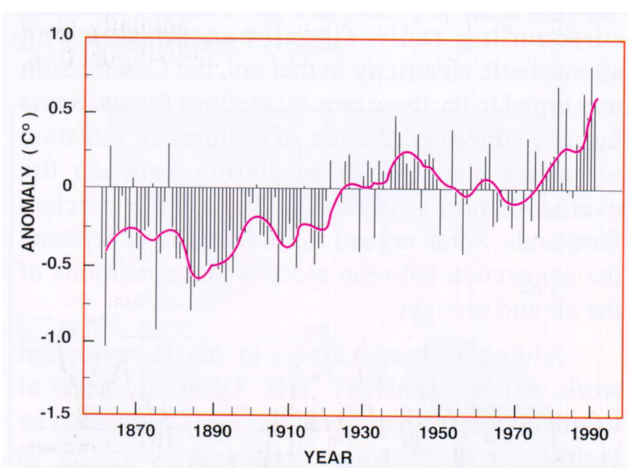


Figure 60: Northern Hemisphere land temperature anomalies, relative to 1951-1980. (Reproduced from Figure C2(a) in CLIMATE CHANGE 19928': graph compiled by D.P. Jones). Even though there is considerable year-to-year fluctuation, the smoothed curve by D.P. Jones hints at an 11-year and an 80year temperature cycle-both of which may be linked to solar activity. The cool period from about 1865 to 1915 and the warm period, 1916 to 1950 may be tuned to the 80-year Gleissberg Cycle mentioned on page 22.

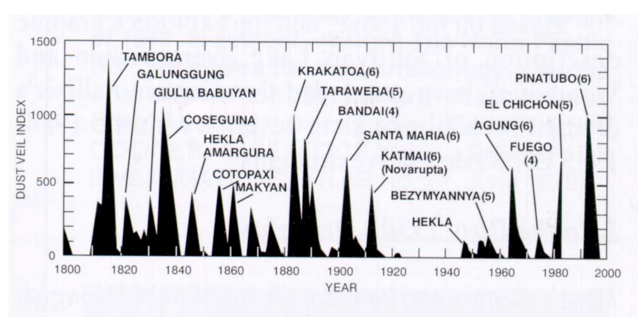


Figure 62: Major volcanic eruptions from 1800 to Mount Pinatubo in 1991 (graph adapted from Simkin's and Fiske's, Figure 130). The dust veil indices and the volcanic explosivity indices (shown in brackets) are reproduced from Robock's and Mao's" Table 1.

PRE-SETTLEMENT DROUGHTS

Prairie Climate From the "Medieval Optimum"to the Construction of the CPR Railway

Although the 1857-1859 Palliser expedition to the Canadian Prairies undertook some temperatures and precipitation observations, the first long-term climatological station was not established until 1883 at Winnipeg. Consequently, it is necessary to rely primarily on proxy data to reconstruct the climate on the Prairies prior to the construction of the CPR Railway and the Experimental Farms. Much of this essential work has been done by several Canadian geographers, paleontologists and geologists. Using the hard-won field results of her own research and that of her colleagues, Alwayne Beaudoin has compiled the significant features of the Alberta climate from the time the glaciers retreated to 1883 when the first CPR train, *"chugged across the Prairies and drew into Calgary. " Three* pre-instrumental climatic intervals are critical to Prairie agriculture:

- the "Medieval Warm Period", c.800 to 1150 AD, when temperatures were warmer than in the 1980's;
- the "Little Ice Age", c.1200 to 1750 AD, when temperatures dropped by one degree, causing even the Thames River at London to freeze-over in the winter; and
- the warm, "Palliser Drought Period", c.1840 to 1860.

Luckman, Robinson and Colenutt have reconstructed a 900 year-long temperature record Figure 63) for the Columbia Icefield area based on tree-ring densitometry.

The Columbia Ice Fields' record reveals that April-August temperatures in western Canada during the final decades of the Medieval Warm Period were about 0.7 degrees Celsius warmer than present temperature. For scores of years during the Little Ice Age temperatures averaged 0.7 degrees cooler than the mean for 1961-90.

It is logical to ask, *"What was happening within the Palliser Triangle during the extremely warm Medieval Optimum? " The* results of paleoclimate investigations by Vance, Mathewes and Clague at Chappice Lake (50 km northeast of Medicine Hat) offer the best clue. They conclude that desiccating droughts ravaged the region during the warm Medieval Optimum. This is not surprising seeing that all the droughts tend to coincide with years of above average temperature. In the preceding parts of this Primer, the link between warm Northern Hemisphere temperature anomalies and Palliser Triangle droughts was demonstrated as was the converse relationship. The droughts of the 1930's and the 1980's were the direct consequence of the unusually warm periods. For example, the latter drought period spawned six of the warmest years on record.

An educated guess suggests that precipitation was much less during the Medieval Optimum droughts than during the 1930's. An analysis of the 1930-37 precipitation record reveals that most areas within the Palliser Triangle had to annually cope with 50 mm less precipitation than now (Figure 64).

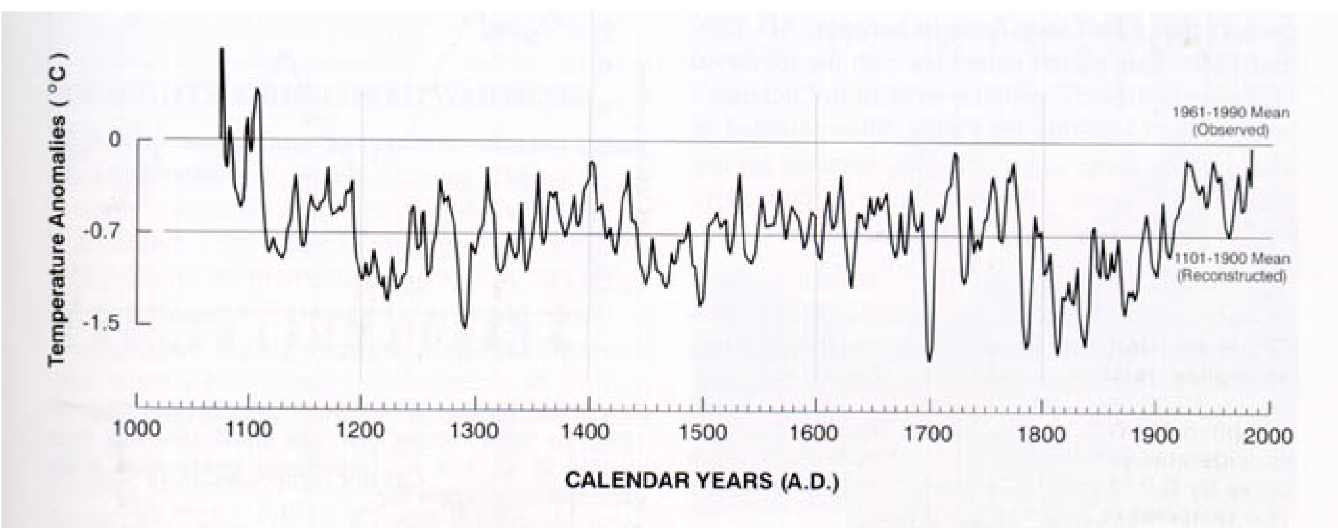


Figure 63: 900 Year Record of Western Canadian temperatures: "Medieval Optimum" to the present. (Graph courtesy Prof. Brain H. Luckman, Department of Geography, The University of Western Ontario).

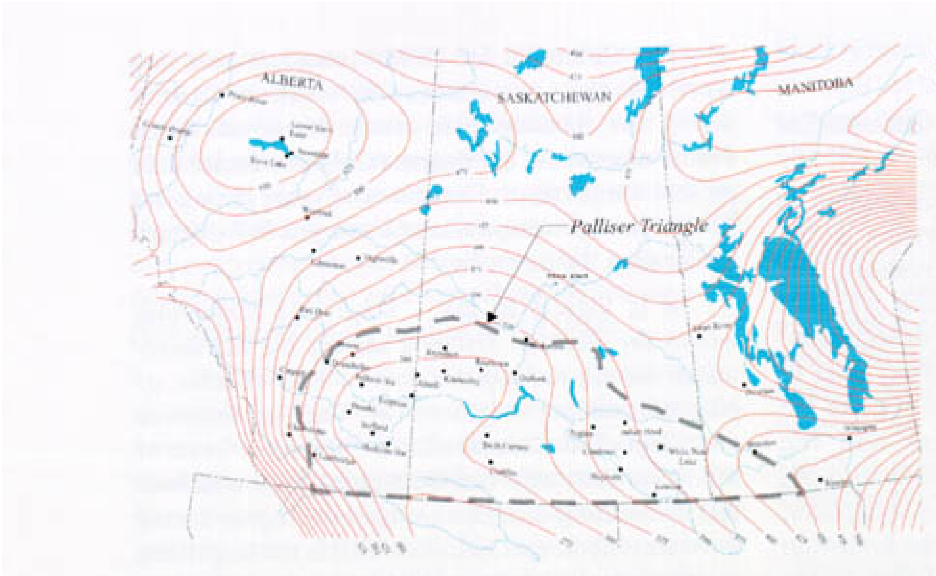


Figure 64: Average annual precipitation within the Palliser Triangle during the 1930-37 drought period.

EVIDENCE OF "SUPER DROUGHTS"

0ne of the disquieting consequences of the 1980's droughts was the exposure of numerous "graveyards" of tree stumps. A number of scientific journals have reported on these discoveries. Several Canadian and American researchers have concluded that our instrumental record is not revealing the truth about the frequency and the persistence of super droughts.

Discoveries in California

New Scientist and other journals have chronicled the discoveries made by Professor Stine of California State University. Stine dated the tree stumps, exposed by declining lake levels, to a century and a half long drought between AD 1200 and 1350. This period coincides with the medieval "Climate Optimum" which is evident in Luckman's work at the Columbia Ice Fields. Stine sounded an alarm about these super droughts because no one knows how much climate change is needed to trigger persistent drought in the USA.

Stine's discovery of the California super droughts is corroborated by a similar dating of a 12th century super drought in the Northern Great Plains, of which the Palliser Triangle is the apex. Nature has published the results of field investigations conducted by Laird, et al

Tree Stump "Graveyards" in Saskatchewan

A four metre decline in the levels of White Bear Lake (Figure 65) near Carlyle, Saskatchewan, exposed several tree stump "graveyards" (Figure 66).

These "graveyards" are mute evidence of a multi-decade long super drought. Andrew Ashford of PFRA's Shelterbelt Centre identified the relic trees as "trembling aspen" (Populus *Tremulides Michx.)*

Studies undertaken by PFRA and the University of Regina suggest that this drought may have occurred about 200 years ago. These investigations are documented by Sauchyn.

The White Bear Lake occurrence is not an isolated discovery. Stine reports that emergent aspen stumps were discovered at Basin Lake, 120 km northeast of Saskatoon, which he carbon dated as being about 200 years old.

Based on dendroclimatic reconstruction of annual precipitation on the Western Prairies, Case and MacDonald conclude that the 1917-1922 was not the most severe drought period in the Palliser Triangle. They found evidence of a decade-long super drought commencing about 1790. Their finding is supported by Sauchyn's and Porter's dendrochrology dating of a super drought in the Cypress Hills during the same time span. This then was the likely period when the trembling aspens grew at White Bear Lake and Basin Lake.

Figure 65: Plot of White Bear Lake levels, 1910 to 1992. In 1988, when the lake level receded four metres to el. 730 m, tree-stump graveyards were exposed (see Figure 66).

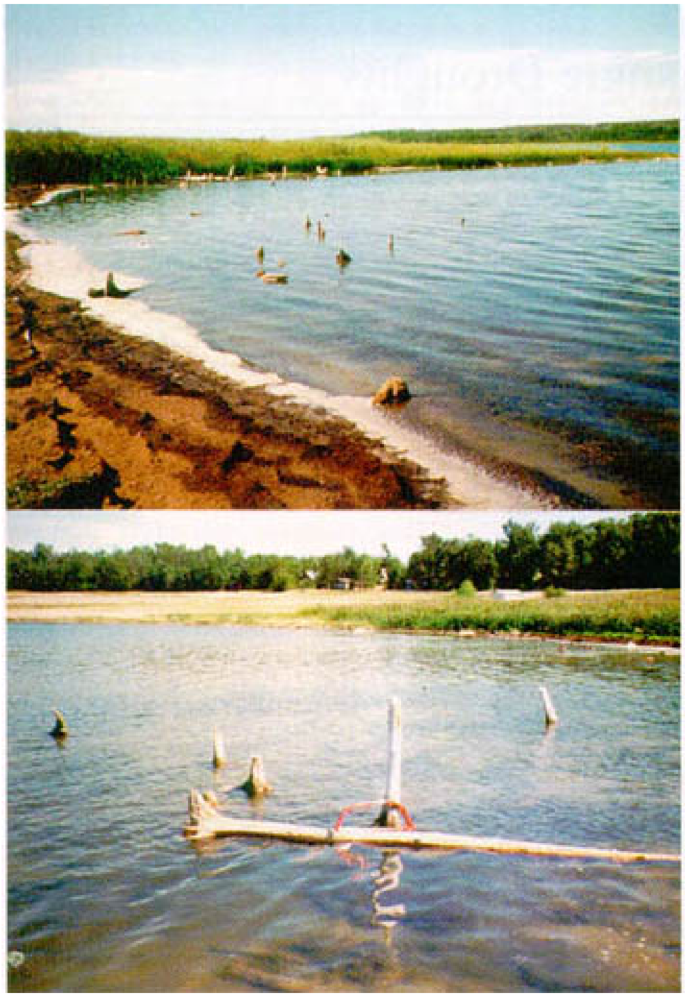


Figure 66: White Bear Lake tree stump graveyard exposed by a 4m decline in water levels between 1976 and 1990. If Mount Pinatubo had not erupted and caused global cooling, and increased precipitation in the Palliser Triangle, young aspens may have already sprouted among these emergent stumps.

DROUGHTS AND GLOBAL WARMING

Environment Canada's recently released report, Responding to Global Climate Change in the Prairies, presents estimates of global warming for a doubled C02 atmosphere. Seasonal-Prairie temperatures are predicted to increase by an average of two degrees Celsius. This would result in temperatures higher than the Medieval Optimum and consequently, major dislocations to Palliser Triangle agriculture. A likely scenario would be a repeat of the Dry Belt disaster. University of Calgary professor, David C. Jones, in two separate books, EMPIRE OF DUST and WE'LL ALL BE BURIED DOWN HERE chronicles the agonies and the hardships of the early dryland homesteaders in southern Alberta during two prolonged droughts: 1917-1922 and 1929-1937. By the time the dust storms of the 1930's had abated, thousands of farms had been abandoned. Authors Gorman (ref. 11) and Gray (ref. 13) have carefully documented the supreme efforts required by the farmers and the three levels of governments to rescue the southern Prairie agricultural sector from total disaster.

Pioneer poet, Mildred Mellen, poignantly recalls the times in a poem published in THE PRAIRIE CRUCIBLE, a history of the small towns which dotted the treeless, shortgrass landscape in the Dry Belt area of southeastern Alberta. Some towns still exist, like Jenner-the site of the Prairie Dust Motel-and Iddesleigh, with it streets named after American Presidents. But most towns have succumbed to drought and depression, like Majestic, with its scenic location and Tide Lake, imaginatively named after a shallow slough that is notoriously dry every drought year. Mildred Mellen described the cooperative spirit of the pioneers in helping their neighbours to salvage their meagre possessions and start life anew (Figure 67):

Each gave a hand to his neighbour, a
link in an unending chain
and together- pressed fbrward to triumph
over drought, and heartbreak and pain.

Figure 67: Neighbours lend real and mechanical horsepower to help a fellow farmer to move his house from drought-stricken Iddesleigh, Alberta. (Photo courtesy Ab Grover and Tom Osadczuk).

Predicting Palliser Triangle Droughts

Weather forecasting has always been the butt of many jokes. A few cartoonists have even invoked some barnyard humour; but if the present level of scientific knowledge of drought forecasting, is judicially exploited, success can be achieved.

"Let's all gather under the tree so he'll think it's going to rain."

(Courtesy of the Canadian Cattlemen Magazine; cartoon by Clair Anderson).

climatological station to record the warmest daytime temperature and be accorded the distinction of being "Canada's hot-spot". Ironically, Milk River, Alberta earned this award on February 24, 1988 (with a record high temperature of 21 degrees Celcius) while local farmers and ranchers met in an old country school house with PFRA and Provincial officials to discuss the need for groundwater exploration and rural water pipelines (see Figure 15).

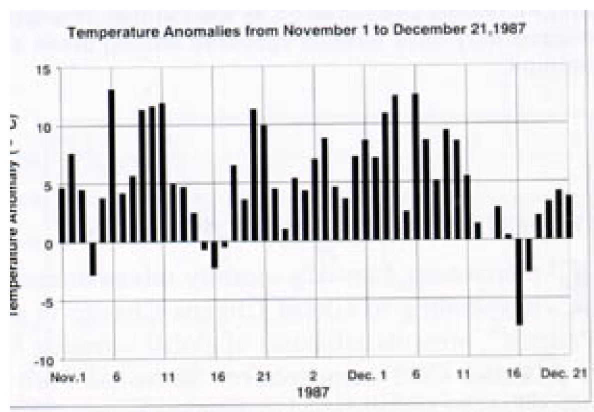


Figure 68: above) Balmy, December 10, 1987, farmyard scene near Craigmyle, Alberta; below) regional autumn, daily maximum, temperature anomalies at Calgary.

THE PROMONTORY DROUGHT SIGNS

As documented in the preceding part, many of the promontory signs of drought have long been known by Palliser Triangle farmers.

Despite its allure, a warm dry fall has usually been a harbinger of drought. Invariably, these benign conditions would continue into early winter, much to the relief of farmers and ranchers wintering their herds outdoors. Frequent chinooks would sublimate much of the meagre snow pack, permitting winter range grazing. Figure 68, taken near Craigmyle (Alberta) December 10, 1987, shows the balmy early winter conditions; however, these were the precursors that heralded the exceptionally severe 1988 drought.

Many experienced ranchers dubbed these conditions, "Winter Drought". Typically, soon after New Year's day, warm dry spring-like weather would arrive weeks before the vernal equinox. During these extremely mild winters, it would not be unusual for some Southern-Alberta

Armed with a basic knowledge of the foregoing precursors, any alert drought forecaster could have been in a position to develop long-range drought forecasts decades ago. One such case is high lighted in the next section.

SOUTH SASKATCHEWAN RIVER RUNOFF FORECASTS

During the period 1971 to 1975, the Prairie Provinces Water Board (PPWB) studies on Streamflow Forecasting were conducted. One study resulted in the development of an unique, long range water supply forecasting procedure. It featured an improved regression equation forecast, of South Saskatchewan River spring and summer runoff, using a derivative of the North Pacific Ocean temperatures. It was named, "The Integrating Loss Basin" (ILB) forecasting method. It is described in detail in a PPWB report'°°.

The ILB forecasting method, based on a multiple regression equation, uses as one of the independent variables, the normalized spring snowmelt runoff from small gauged watersheds within the Palliser Triangle of Southern Alberta. A simple, graphical illustration of the method is provided in Figure 69. The curve shows the functional relationship between the forecast residual (of conventional, three variable, regression forecasting equations) and the spring runoff of the ILB basins.

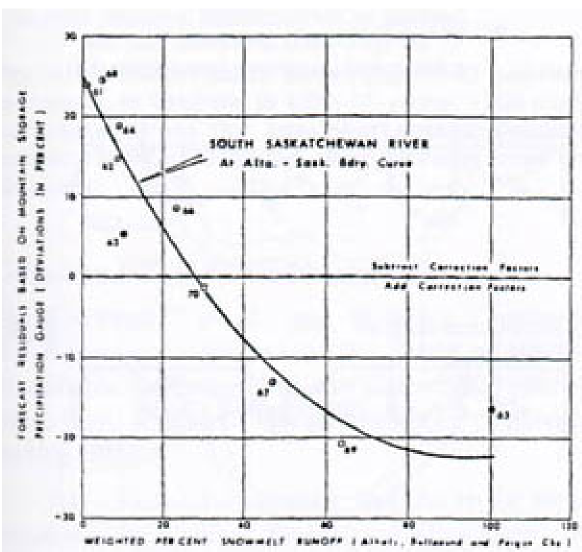


Figure 69: Curve relating 3-variable regression forecast residuals to the ILB spring snowmelt runoff.

The ILB forecasting method derives its accuracy from being able to quantify the effects of all the early drought warning signals relating to low antecedent moisture and the persistence of low precipitation. These effects are primarily attributable to a positive 4-Pt PNA Pattern which causes the Prairie droughts. Conversely, if the pattern is negative, more precipitation and more runoff occurs.

RELEVANT INVESTIGATIONS

Linking SST's To Prairie Precipitation

The relationship between the North Pacific SST's was subsequently investigated by Nemanishen and Meers for the Lesser Slave Lake region in Central Alberta. They found that the net inflow into the lake was inversely related to the North-Pacific SST's (Figure 70).

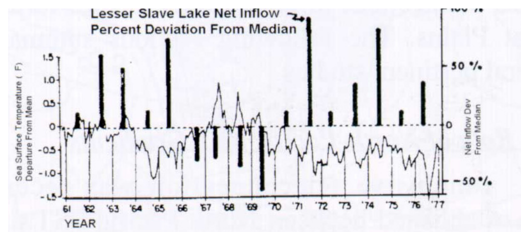


Figure 70: Graphical relationship between Lesser Slave Lake net inflow and Pacific-North American SST's. (PNA pattern Point. 3 is at Lesser Slave Lake).

These studies were extended to establish the correlation between the lake inflow and El Nino conditions. At Dr. Jerome Namias' recommendation, separate correlations were conducted between the warm El Nino and the cold La Nina ocean temperatures measured at Puerto Chicama, Peru. The results of the E1 Nino correlations, shown in Figure 71, demonstrate that:

A high inverse correlation (r= up to 0.8) exists between anomalously high autumn (September to December SSRs)
El Nino temperatures and spring snowmelt runoff. The physical explanation is simple-the late autumn and winter jet stream shunts the snowstorm across Northern Alberta;

- 2. A high positive correlation (r= 0.6) exists between the autumn anomalous El Nino temperatures and rainfall runoff the spring and summer months of the following year. Earlier in this Primer it was shown how the jet stream tends to deflect spring and summer rain storms into Northern Alberta during El Nino years.

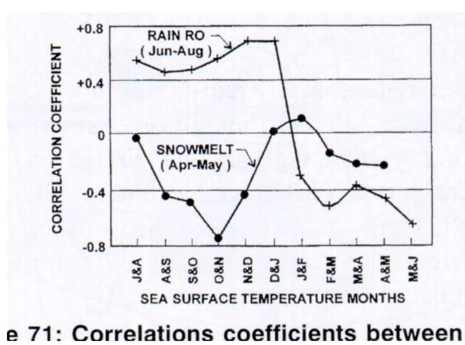


Figure 71: Correlations coefficients between Puerto Chicama SST's and runoff into Lesser Slave Lake. The antecedent, August to December, SST's correlate well with the April-May snowmelt runoff. May to August, summer runoff is related to the October to January SST's. Both correlations suggest that there may be about a six month lag in the teleconnection.

RECENT STUDIES WHICH HAVE CREATED THE ESSENTIAL KNOWLEDGE BASE

In the last decade, many investigators have contributed to the present wealth of information on the ENSO teleconnections to climate extremes around the globe. A number of researchers, like Keplinger and Mjelde'°', have assessed the drought related impacts on cereal crop production; however, the studies which are relevant to this Primer are the ENSO connections to the weather of the Northern Great Plains. The following sections summarize several pertinent studies.

The Role of North-Pacific SST Gradients

A conclusive teleconnection was recently established between North Pacific SST's and growing season extended dry spells on the Canadian Prairies by Bonsai, Chakravarti and Lawford. Figure 72 is reproduced from their paper. It illustrates that the dry spells are created by a positive SST anomaly gradient (lower SST anomalies in the east-central North Pacific and higher anomalies along the west coast of North America). They concluded that the longer the positive anomaly gradient persists, the greater the probability of a major extended dry spell. A persistent nine-month anomaly guarantees a dry spell. Dr. Bonsai hypothesizes that there is a feedback mechanism between the Aleutian Gyre and the gradient regions. The authors cautioned that further research was needed to identify the precise physical processes and recommended that it include analysis of the upper long-wave patterns, the investigation of the possible role of snow cover, solar variability and ENSO. They advised that the wet spells be included.

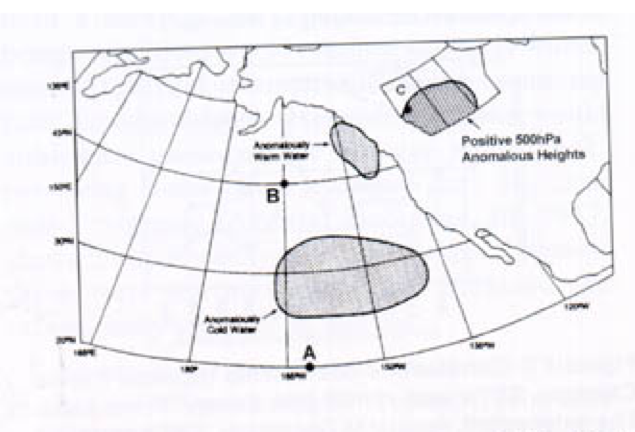


Figure 72: Typical SST anomaly pattern in the North Pacific Ocean and the typical 500 hPa anomaly pattern over the Canadian Prairies during drought.

The Connection Between North-Pacific Atmospheric Circulation and Streamflow

Cayan and Peterson were perhaps the two earliest researchers to correlate the runoff of western USA streams and the sea-level pressures over the North Pacific. Their study area extended Wallace's and Gutzler's PNA region (Pts A, B and C in Figures 27 and 72) to include the Central-North Pacific (CNP). The latter is the ocean region straddling the long chain of Aleutian Islands.

Not surprisingly, Cayan and Peterson found that one of the streams best tuned to the atmospheric circulation in the North Pacific (as defined by either the PNA index or the CNP index) was the Clark Fork at St. Regis, Montana. Based on the three dominant winter atmospheric flow patterns (a, b, and c reproduced in Figure 73), they concluded:

- a) when the CNP low is weak, storms tend to be carried inland by strong-zonal jet stream flow;
- b) when the CNP low is well developed (see Figure 52), storms tend to be carried toward northern BC, leaving northwestern USA dry; and
- c) in strong ENSO years, the American southwest receives heavy precipitation because of the combined moisture brought by the split-polar jet stream and the subtropical jet stream (see Figure 54).

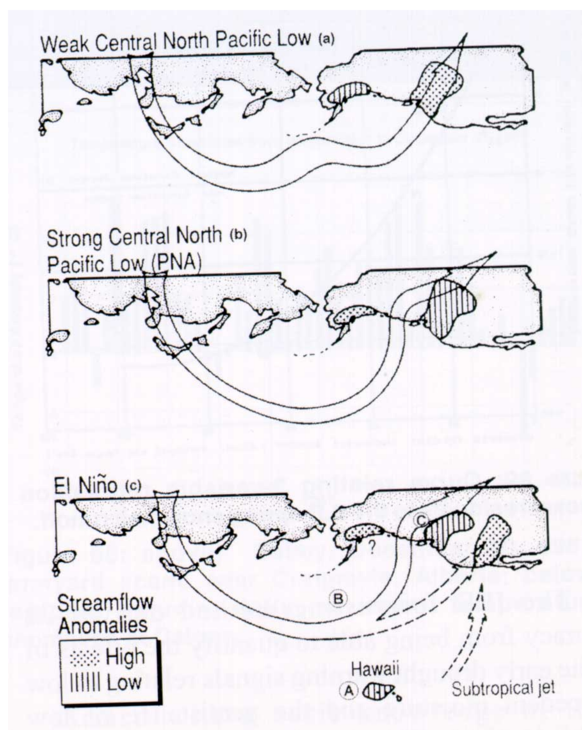


Figure 73: Cayan's and Peterson's schematic of winter atmospheric flow and associated streamflow anomalies during weak Central North Pacific lows, strong Central North Pacific lows, and during the winters of a "mature" phase of El Nino. (PNA points A, B and C are plotted).

The winter sea-level pressure pattern responsible for the cold, heavy-snowfall Prairie winter of 1968-69 is shown in Figure 74(a) while the pattern associated with the mild 1976-77 winter is shown in (b). Pattern (b) represents the late fall and early winter, 1997, Pacific weather circulation responsible for the severe storms which battered the southwestern USA.

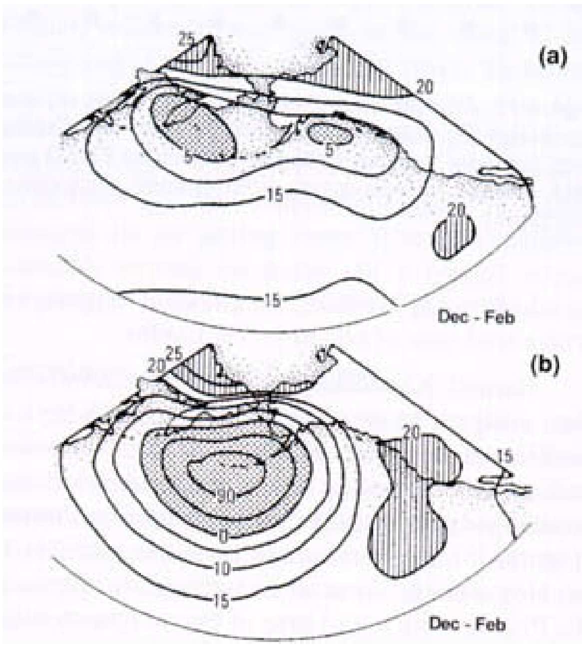


Figure 74: North-Pacific winter (Dec-Feb) sea-level pressures: a) 1968-69, b) 1976-77. (Note: 1000 mb is subtracted from the sea-level pressures. Low pressure areas are stippled-high pressure areas are stripped).

Canadian ENSO Related Investigations

Maybank et al., and Wittrock provide concise overviews of the forces which are precursors to drought in the Canadian Prairies. Since then, additional research has been completed on this subject.

An exhaustive search has recently been conducted by Shabbar, Bonsal and Khandekar to establish the ENSO related precipitation responses over Canada. Using monthly precipitation records from 69 Canadian sites, they first calculated three month moving means and then standardized these means by subtracting the average seasonal values and dividing the difference by the standard deviation. Maps were then plotted using the composite of standardized precipitation. The results show a distinct pattern of negative precipitation anomalies occurring in the Prairies during the first winter following the onset of El Nino (Figure 75a) The precipitation anomalies are positive for La Nina events (Figure 75b). They expressed this conclusion:

"All of~the significant precipitation anomalies can be explained by the associated upper atmospheric flow patterns which during the first winter following

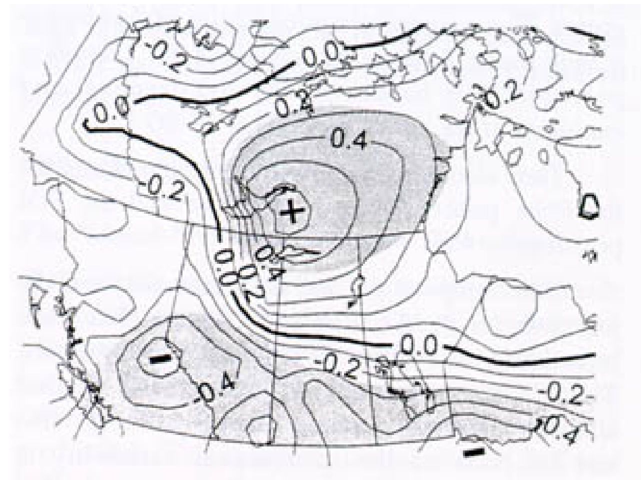


Figure 75a: Composite of standardized precipitation anomalies for January-to-March season following the onset of an El Nino during the preceding fall.

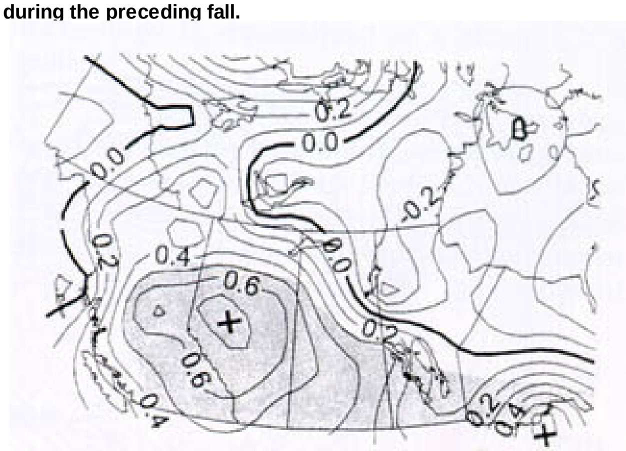


Figure 75b: Same as (a) but for La Nina.

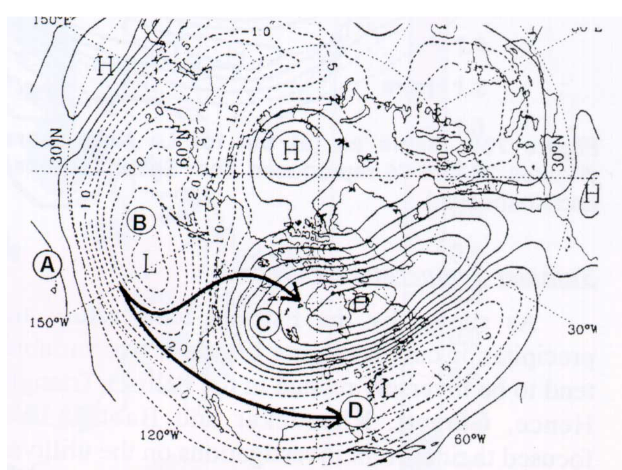


Figure 76a: JFM (+1) composite 500 hPa anomalies (in metres) associated with El Nino. Negative contours are dashed. Arrows show the split-jet streams.

the of El Nino ... events, resemble the positive ... phase of the Pacific-North American (PNA) pattern. Results Indicate a build-up of negative Southern Oscillation Index (SOI) values prior to the observed precipitation anomalies during the winter following the onset of El Nino events. This suggests the possibilities of developing a long-range,forecasting technique for Canadian precipitation based on the occurrence and evolution of the various phases of ENSO. "

They also note that after the onset of La Nina, the PNA pattern becomes negative and the SOI positive.

Their maps of the 500 hPa anomalies and the jetstream for the El Nino and La Nina phases are reproduced in Figures 76a and 76b respectively. These three experts recommend that further analysis be done to determine the impact of El Nino and La Nina on the inter-annual variability in Canadian precipitation and they advocate that individual ENSO events be studied with respect to intensity, duration and spacial extent.

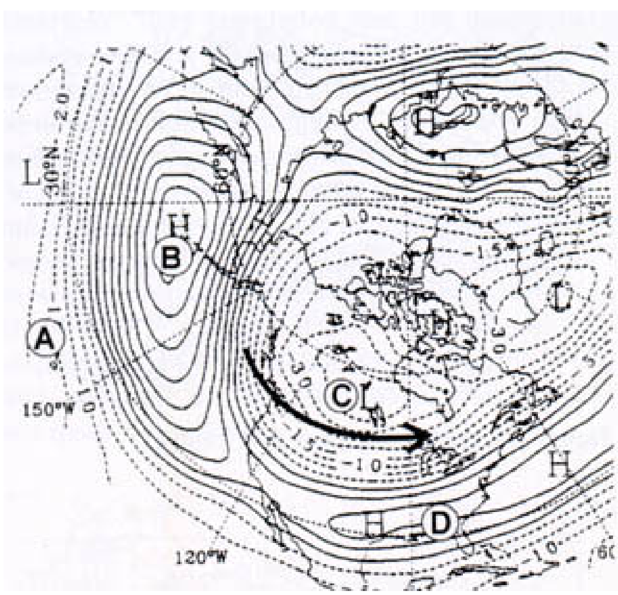


Figure 76b: Same as (a) but for La Nina years. (Figures 75 and 76 reproduced from Shabbar, Bonsal and Khandekar).

Summer Temperature Forecasts

As shown by the Estevan temperature and precipitation curves (Figure 17), these two variables tend to be inversely related in the Palliser Triangle. Hence, Garnett, Khandekar and Babb '°' have focused their current investigations on the utility of using ENSO and the Pacific North America (PNA) indices for forecasting summer weather over the crop growing region of the Prairie. Their results demonstrate that these predictors can be utilized to

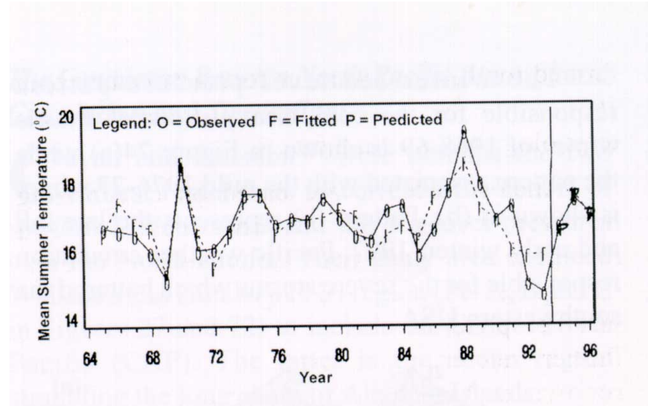


Figure 77: Comparison of observed (0), fitted (F) and predicted (P) summer temperature over the Prairie crop growing regions. Forecasts based on ENSO and PNA indices. (Reproduced from Garnett, Khandekar and Babb).

foreshadow the summer temperature (Figure 77) with a lead time of two to seven months.

Garnett, Khandekar and Babb have reinforced their analyses by empirical procedures which yield profiles of accumulated monthly teleconnection indices for the hottest and coldest, or driest and wettest summer months over the Canadian Prairies (Figure 78). They conclude that it is possible to develop a skillful forecast of summer weather over the Prairies with a lead time of two to four months.

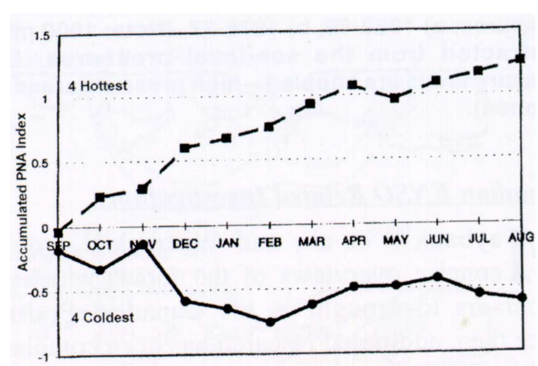


Figure 78: Composite of accumulated PNA Indices for the four hottest (1988, 1970, 1989, 1987) and for coldest (1993, 1992, 1969, 1985) June-July periods on the Canadian Prairies.

THE FORECASTING TECHNOLOGY

There are currently three basic drought forecasting technologies: analog procedures, correlation equations, and computer models. The merits of each technology is briefly described next.

Analo$ Forecasts

Analog forecasting procedures are among the oldest, having been used by Benjamin Franklin and shortly thereafter refined by the editors of THE OLD FARMER'S ALMANAC. Analog procedures formed the basis of weather forecasts since about 1930. In the hands of experienced forecasters, this technology ranks with the best.

Analog forecasts are based on categorizing historic weather events into distinct and recognizable patterns. Because the ocean atmosphere represents a huge analog computer, weather patterns tend to repeat. Earlier in this Primer, reference was made to the work of the renowned American meteorologist, Dr.Irving Krick, and the West German expert, Dr. H.J. Liebscher, two of the world's leading experts on analog forecasting. In Canada, the analog procedures are still extensively used. A classic example of an analog forecast is Environment Canada's current prediction of atypical winter temperature response to El Nino (Figure 79).

Correlation-Equation Forecasts

Multiple regression technology has been used since the 1950's to forecast seasonal streamflow runoff. Historic data is used to derive a three or four variable, mathematical forecasting equation. Forecasts can be quickly computed and their accuracy is directly linked to the accuracy of the input data.

More recently, the regression technology has been greatly improved by the development of the Canonical Correlation Analysis (CCA) described by Shabbar and Barnston. CCA analysis has the ability to mathematically capture the pattern-to pattern relationship between large-scale predictors and the predictand. The authors report that by using the CCA technology, seasonal forecasts of surface temperatures and precipitation have been achieved for lead times of up to one year.

Although a very powerful technology, CCA does not fully explain the nonlinear relationships which are encountered in weather related phenomena.

Computer-Forecasting Models

The Neural-Networks Computer Technology

In Canada, seasonal climate predictions are made for the country by the Canadian Institute For Climate Studies (CICS) located on the campus of the University of Victoria, at Victoria, B.C. A "Neural-Network" Model is used to make the predictions. This computer model utilizes SST and SOI data to predict seasonal precipitation and temperatures.

The power and advantages of neural-network technology is summarized in a recent CICS bulletin:

"The ability of neural networks to recognize and reproduce complex patterns from large data sets make them ideal tools for application to the ENSO-climate anomaly problem. They can simulate the linear and non-linear relationships between physical events (e.g., warming/cooling of tropical

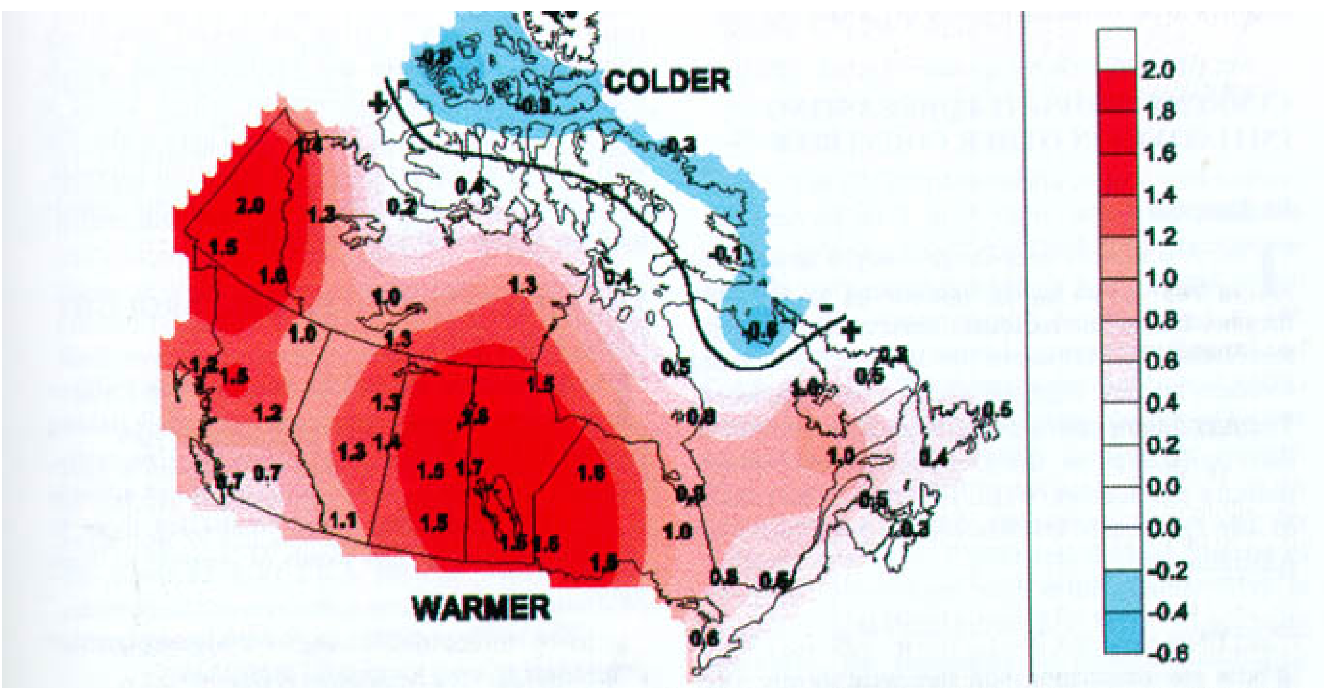


Figure 79: Typical winter response to El Nirio. (Reproduced from The Canadian El Nirio Bulletin by Amir Shabbar and David Phillips of AES).

surface water) and a downstream response (e.g., air temperature anomalies over Western Canada) in situations where specific details of the underlying relationship are not well understood. For these reasons, CICS has chosen neural networks to simulate seasonal climate conditions for Western Canada using ENSO as the source of the seasonal climate signal. "

CICS currently prepares seasonal climate forecasts on a monthly basis for its members, including PFRA. The CICS forecast of 1997 winter precipitation is shown in Figure 80.

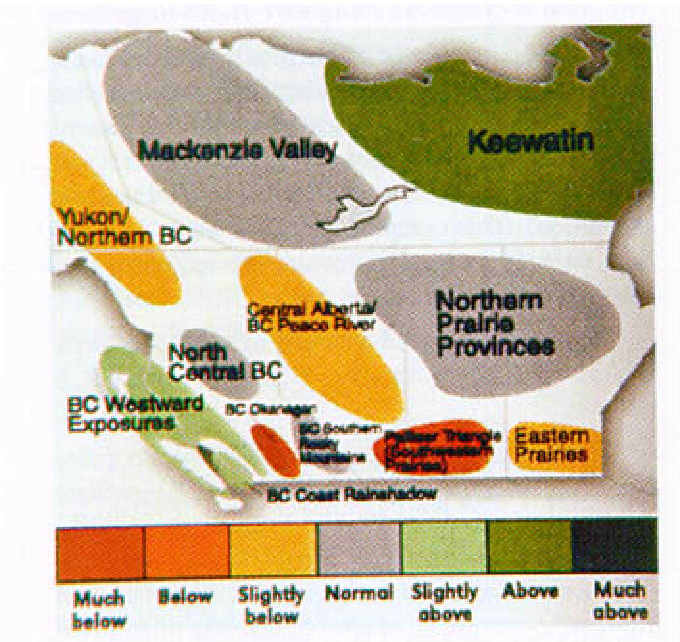


Figure 80: Winter 1997 precipitation forecast (data courtesy of the Canadian Institute of Climate Studies).

CURRENT DROUGHT FORECASTING INITIATIVES IN OTHER COUNTRIES

In Australia

The Australian's long-range drought forecasting initiative was nearly operational by the time they hosted the International Conference on drought forecasting in Melbourne in 1991. ENSO based forecasts are now regularly prepared and published. The Australians provide a very readable account of their initiatives in the Department of Primary Industry publication, WILL IT RAIN? The Effects of the Southern Oscillation and E1 Nillo on Australia.

In India

i ndia pioneered monsoon forecasts shortly after the turn of the century using various ENSO derivative variables. A comprehensive description of the forecasting procedures is provided in the publication, THE SOUTHWEST MONSOON, and in Dr. Khandekar's paper (Reference 74) on the Indian Monsoon and World Grain Yields.

In the U.S.A.

Various American government agencies, like the Weather Bureau and NOAA, prepare various long-range forecasts. These can be consulted on the Internet.

A number of weather consulting firms, like Weather Trades Inc., and AccuWeather Inc., provide specialized forecasts to subscribers. Some commodity brokers retain meteorologists to assist their clients in judging weather impacts on commodities.

In Israel

The recent Israeli break-through in long-range drought forecasting is described in the NEW SCIENTIST report, "Pacific Upheavals Relieve Israel's Drought". Forecasters in the Weizmann Institute at Rehovot found that winter rainfall rises sharply in the hills of Israel during years when El Nino causes drought in Australia and storms in South American deserts (NS, p. 13, 6 July 1996). The Bible contains accounts of heavy rainfall and rainfall periodicity that were likely linked to El Nino. The recently discovered teleconnection with El Nino might explain the rainstorm which occurred in the wheat harvest (1 Samuel 12:16-18) when it is traditionally dry. Elijah observed towering cumulous clouds over the Mediterranean which were precursors to a downpour which broke a severe drought (1 Kings 18:41-45). There is also the well known seven-year cycle of bountiful harvests. The latter was probably a result of the quasiperiodic seven-year El Nino cycle.

THE CHALLENGE TO PRAIRIE DROUGHT RESEARCHERS

o embark on an initiative to develop Palliser Triangle drought forecasts will entail risking failure. Yet the President of Princeton University, Harold T. Shapiro, in his commencement address to the 1990 graduating class, counselled them to take informed risks. His words of wisdom to them were:

"The willingness to risk failure is an essential component of most successful initiatives. "

Summary, Conclusions and Recommendation

Part 1 of this Primer briefly dealt with the precarious nature of farming in the lowest rainfall area of the Palliser Triangle, the Dry Belt. As a consequence of a seven-year drought, 1917 to 1923, grain farming essentially ceased in the southern sector. The droughts of the 1930's greatly added to the area of abandoned farms. The droughts of the 1980's demonstrated that dryland farming in all of the Palliser Triangle was still at the mercy of prolonged droughts.

Part 2 explored the role of the ENSO phenomena in contributing to drought. Evidence was presented which demonstrated that the Southern Oscillation and El Nino, and their derivatives, are the primary drivers of drought around the world. The Aleutian Gyre, a derivative of ENSO, figures prominently in Palliser Triangle droughts. Wind currents and ocean currents convey warm tropical waters into the Gulf of Alaska during the ENSO months to create an enormous source of energy which sustains a huge low pressure system in the Gulf, but the details of the conveyance system are not yet fully deciphered. For months, this becomes one of the four dominant atmospheric circulation features, which collectively are denoted the positive 4-point Pacific-North American (PNA) pattern. Since all the weather related processes derive their energy from the solar radiation which reaches the earth's surface, factors which effect this critical variable were identified. Recent studies have established a link between solar activity and weather but further research is needed to explain the processes. Precise measurements show that the sun's luminosity varies cyclically. A complicating factor in these studies are the transient dust veils created primarily by mammoth volcanic eruptions. Radiation measurements reveal that the dust veils can screen-out up to 25% of the solar energy.

Part 3 identified the salient features of the Prairie-grain belt climate, including the areal extent of historic drought years. The most severe drought in the last 50 years occurred in 1988. Its origin was the positive 4-Pt PNA pattern which became established the preceding autumn. This pattern was a derivative of the 1987 ENSO.

Part 4 collated historic evidence to demonstrate that not only was the drought observed by Captain Palliser, but also those of the 1930's were linked to ENSO. During the latter drought period, a clear atmosphere allowed higher than average solar radiation to reach the earth's surface and sustain the weather factors conducive to perpetuating drought. Evidence was also presented of earlier and much more severe droughts but their exact cause(s) are still conjectural.

Part 5 presented some of the forecasting investigations and studies currently underway to improve and advance our understanding in this area. It showed that Canada lags only slightly behind Australia, India, Israel and the USA in drought forecasting technology. However, we now have in hand most of the prerequisite scientific knowledge.

CONCLUSIONS

1. Based on numerous scientific investigations relating to Prairie droughts, the ENSO phenomena, solar radiation, and the Pacific-North American weather patterns it is evident that:

a) The Prairies continue to be vulnerable to droughts; b) Droughts are riot random events;
c) The origin of Prairie droughts are the weather systems spawned by Pacific-North American SST's and air- pressures arid sustained by the 4-Pt PNA Pattern;
d) The drought causing weather patterns are now recognizable and can be used to predict drought.

2. The ENSO phenomena is now well known. At intervals of 3 to 7 years, sea-level pressures reverse between Tahiti and Darwin (Australia), the easterly tradewinds weaken or reverse, and within months, the warm waters accumulated in the Indonesian region, spread eastward to Central and South America. The strength and duration of ENSO is very variable, perhaps as a consequence of factors related to the radiant energy fuelling the process. This energy is related to cyclical variations in the sun's luminosity and atmospheric screening by volcanic dust veils. ENSO acts through a series of derivative phenomena, such as the Aleutian Gyre, in contributing to Prairie droughts. As global warming increases, the frequency of droughts and their durations will also increase.

3. It has now been conclusively demonstrated that ENSO droughts tend to occur simultaneously in drought-prone regions around the world. The weather patterns are known to establish broadbased cause-and-effect relationships to generate timely drought forecasts.

4. With the advent of geostationary weather satellites, the Aleutian Gyre can be observed daily. Since it is essentially a huge heat engine powered by the warm El Nino waters, it lends itself readily to temperature measurements needed as input to drought forecasting equations. Furthermore, its effects on the atmospheric pressure patterns is known and its relationship to the split-polar jet stream is well documented. These factors can improve the predictive equations.

5. Long-range drought forecasts for the Canadian Prairies are now within easy reach but it will take the combined and coordinated efforts of various investigators and their respective agencies. The following recommendations are therefore offered in the spirit of scientific advancements.

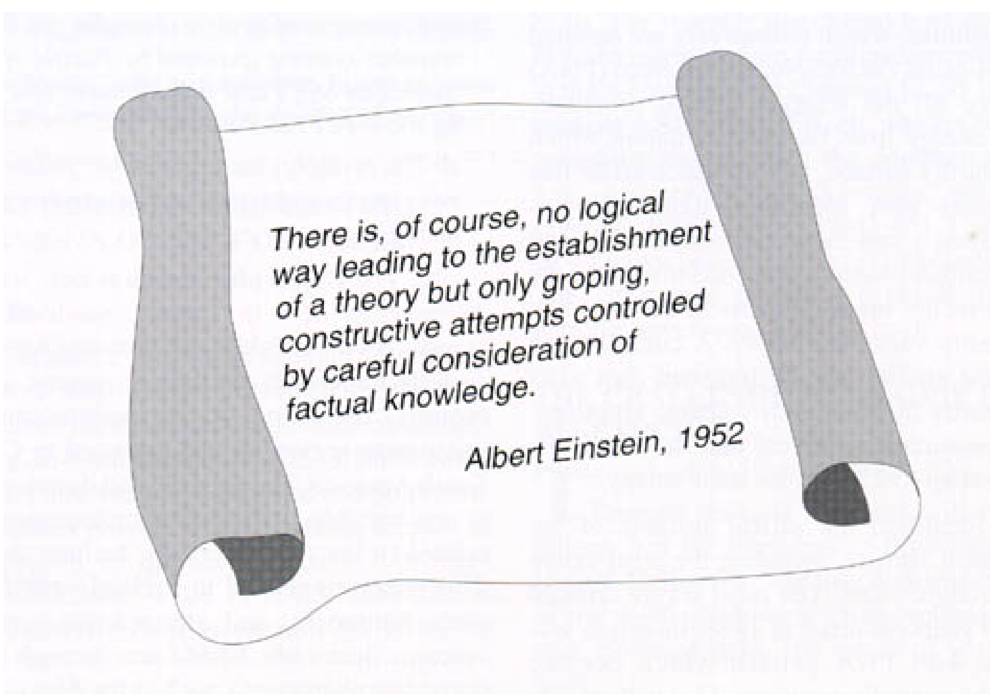
RECOMMENDATIONS

1. No Canadian agency, be it government or university, has a clear mandate to conduct Palliser Triangle drought research. The extremely strong, 1997 El Nino, has obviously prompted a series of uncoordinated studies. Since PFRA has always had a Prairie-wide mandate to deal with drought, and has partnered with its provincial counterparts on relevant initiatives, PFRA should offer its services in convening a drought-forecasting strategy meeting. The invitations should extend to University and government drought investigators, to officials of the Canadian Institute of Climate Studies, and to the members of the Long-Range Weather and Crop Forecasting Work Group. This convocation would be tasked with identifying knowledge gaps in the drought-driver processes, and in formulating a strategy, workplan and budget to attaining operational drought forecasts.

2. The ongoing initiative of Garnett, Khandekar and Babb to forecast Palliser Triangle summer temperatures should continue to be encouraged and supported.

3. Scientists at the Canadian Climate Centre should be consulted to determine if any of the current Global Circulation Models can be adapted to predict the dominant features of the Aleutian Gyre.

4. Further proxy-data research should be conducted to quantify the severity of the 18thcentury super drought and of the medieval-optimum drought.



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geomagnetic disturbance lasting 9-10 hours was observed and ionosphere records indicated a rise in radiowave absorption, followed one hour later by a sharp drop in F-2 critical frequency (the frequency above which radio waves completely penetrate the F-2 layer). At 1700 UT on the 22nd, very low critical frequencies, about 4.5 megacycles per second, were observed in the F-2 region; critical frequencies did not reach the normal eight-megacycle level until 1700 UT on the 25th.

The onset of warming at the 10-millibar level was nearly concurrent with the beginning of the geomagnetic and ionosphere disturbances . ... It is interesting to note that warming of nearly equal magnitude to that over the South Pole region swept over a large portion of Antarctica within a 24-hour period beginning on October 22nd . ... Plots showing the time of occurrence of maximum temperature at 50 millibars over a number of Antarctica stations also suggest this pattern of change."

As the zenith of the Gleissberg, 80-year solar cycle approaches, it is anticipated that spectacular displays of the aurora borealis will become common. A recent report on the Brownfield (Ab.) weather by Bud Bargholz, in THE REVIEW, (Coronation, Ab., Tuesday, December, 2, 1997) described a recent auroral display: "Did anyone see the Northern Lights on the night of November 22? I've seen a lot of these lights over the years, but nothing to compare to that night and they were bright for hours!"

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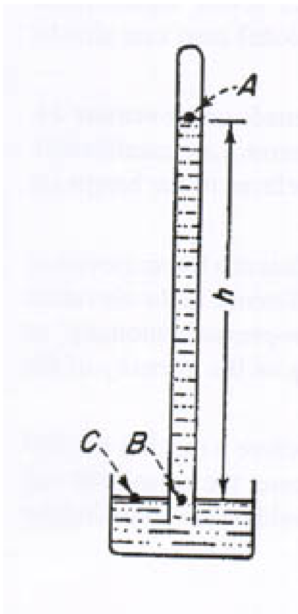
Appendix A: Atmospheric Pressures

1. The Way Atmospheric Pressure is Measured and the Units ofMeasurement



A mercury barometer

The first barometer was made by the Italian physicist, Evangelista Torricelli, in 1643 from a long glass tube sealed at one end. Filling the tube with mercury and turning it up with the open end in a bowl of mercury, he found that although the column of mercury in tube fell (A), it tended to remain at a height of about 29 inches. Torricelli correctly reasoned that the weight (B) of the mercury column (h) in the tube was being balanced by the atmospheric pressure (C) on the surface of the mercury in the bowl.

In 1648 the French scientist Blaise Pascal found that the mercury column in a barometer dropped slowly as it was carried up a mountain. Another barometer at the foot of the mountain showed the same reading all day. This was because the atmospheric pressure falls the higher the barometer is above sea level. At height of 30 km, the mercury column is only about 7 mm, which in meteorological terms would be denoted 7 millibars (7 mb).

Many years ago, the unit of standard atmospheric pressure became the atmosphere, which at sealevel can be expressed by the following relationship:

1 atmosphere (atm) = 76 cm mercury = 29.92 inches of mercury

Most household aneroid barometers are graduated in "inches" . At sea level locations, intense low-pressure systems (associated with storms) can cause the barometric pressure to drop from the standard 29.92 inches of mercury to about 28 inches. During dry, air-weather days, the barometric pressure rises to about 31 inches of mercury

Until the adoption of the SI system of measurements in Canada about 15 years ago, atmospheric pressure was expressed in the unit of millibars (mb), named after bar-type mercury barometer. The unit represent 1/1000 the column height of the mercury. When the SI measurement system replaced the Imperial measurement system, the "millibar" unit of atmospheric-pressure designation was replaced by the Pascal (Pa) unit with the following relationship and SI prefixes:

1000 mb - 1000 hPa (1000 hecto-Pascals) = 100 kPa (100 kilo-Pascals)

2. Pressure Surfaces in the Atmosphere

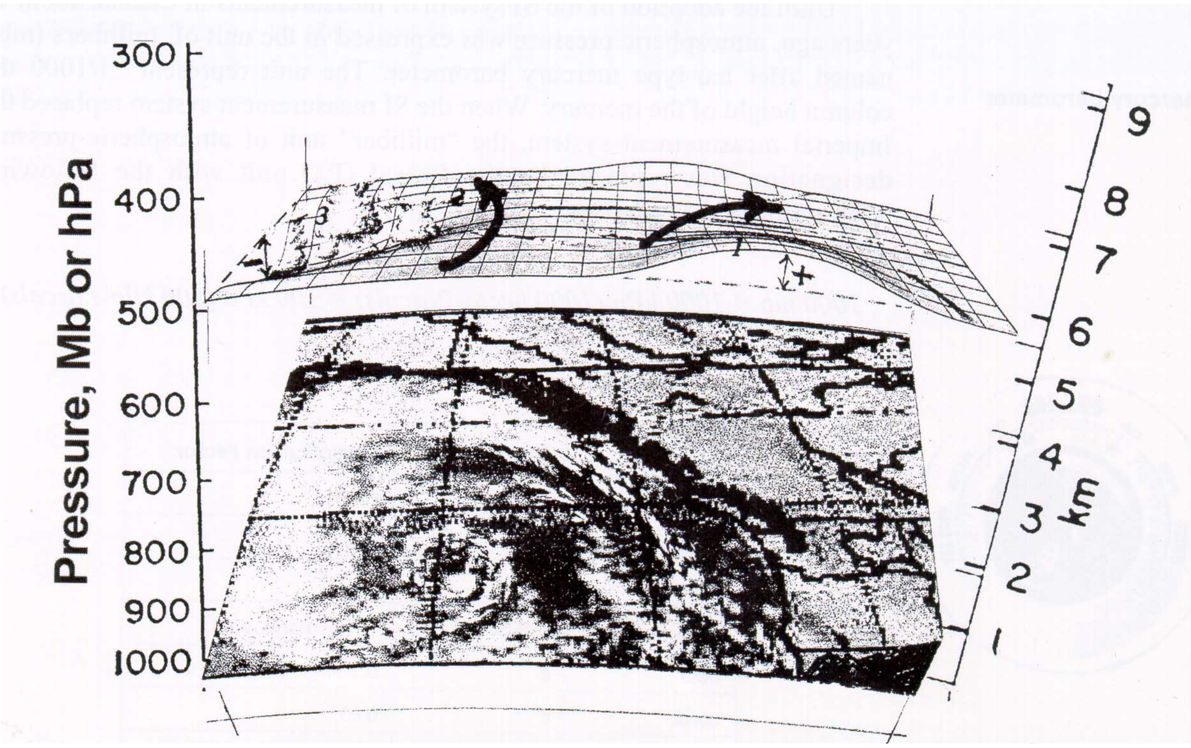
With the development of radiosonde technology in the 1930's, meteorologists began monitoring the temperature, humidity and pressure of the atmosphere at regular times during the day. The name of this device is based on. the French word sonde, the term for a sounding line to measure water depths. Radiosondes which are tracked by radar to measure upper-air wind speeds and direction, are called rawindsondes. Radiosondes are carried aloft by large balloons and transmit their data by radio to a weather station.

Based on the data radioed to earth by 1000's of radiosondes released daily around the world, meteorologists compile weather maps for certain levels in the atmosphere, usually at the following pressure surfaces: a) 700 mb, 500 mb, 300mb, 200 mb, 150 mb, 100 mb and maybe 50 mb if the radiosonde balloon has not burst. Meteorologist prepare weather maps for certain pressure-surface levels which show temperatures, relative humidity, wind speed and wind directions. A three dimensional map can also be drawn for any given surface.

An artist's sketch of the 500 mb surface over the Gulf of Alaska and western Canada on November 14, 1997, is reproduced below. At this level (eg., about 5600 m) much of the storms's dynamics are manifested). The composite sketch illustrates the general relationship of the various pressure surfaces to the height (in kilometres) above sea level.

Over the Aleutian Gyre, the radiosonde would have intersected the 500 mb surface at a lower elevation because because of the large, low-pressure zone of stormy weather. The numeric difference in the elevation of 500 mb surface and the standard height for this surface, would represent the "low-pressure anomaly" at point 3. This negative anomaly could be in the order of 10 to 100 metres depending on the intensity of the storm.

Over Alberta-BC, the radiosonde would have ascended to a higher elevation before it reaches the 500 mb surface because was ascending through a dome of cooler, denser air. In this case, the actual 500 mb surface could have been up to 100 m higher than the standard surface. This then would be the so-called the "positive height anomaly" at point 1.



An artist's 3-D sketch of 500-mb pressure surface over western Canada (1) and the Gulf of Alaska (3). The negative height anomaly over the Aleutian Gyre and positive height anomaly over western Canada are shown by the bold minus sign (-) and bold plus sign (+) respectively. The jetstream usually occurs well above the 500 mb surface.