4.11 LARGE SCALE ATMOSPHERIC CIRCULATIONS AND POLAR LOW GENESIS OVER THE GULF OF ALASKA

Boniface J. Mills* and Mark R. Anderson
Department of Geosciences, University of Nebraska - Lincoln

1.0 Introduction

Intense mesoscale winter storms over water, polar lows, are non-frontal weather systems that occur in very cold air masses. Polar lows have been studied for over forty years by various researchers (e.g., Harley 1960; Pedgley 1968; Harold and Browning 1969; Reed 1979; Locatelli et al. 1982; Wilhelmsen 1985; Businger 1985, 1987; Reed and Blier 1986a, b; Bromwich 1987; Turner and Warren 1988; Yarnal and Henderson 1989; Bond and Shapiro 1991; Leider and Heinemann 1999; Harold et al. 1999). High resolution satellite imagery has improved our understanding of polar lows in the past twenty years. This study focuses on the examination of polar lows over the Gulf of Alaska (Fig. 1.1) and the frequency of polar lows is analyzed with atmospheric and oceanographic teleconnection indices.

* *Corresponding author address:* Boniface J. Mills, University of Nebraska – Lincoln, Dept. of Geosciences, Bessey 214, P.O. Box 880340 Lincoln, NE 68588-0340; e-mail: bonm278260@aol.com

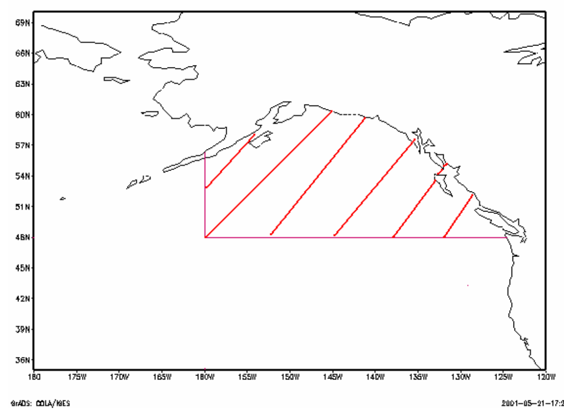

Fig. 1.1. Map of study area; the red hatched box is the polar low study area over the Pacific Ocean.

Polar low frequencies around Antarctica were influenced by large-scale atmospheric and oceanographic changes between 1977 and 1983 during the winter months (Carleton and Carpenter 1990). More importantly, the changes in frequency occurred during the time of the El Nino/Southern Oscillation (ENSO) of 1981-1983 and the amplification and weakening of the southern circumpolar vortex. Carleton and Carpenter (1990) indicated that polar low frequency around Antarctica changes with long-wave pattern change using the Meridional Index (MI) and the Trans-Polar

Index (TPI). Strong upper-level waves and a positive ENSO event are associated with increased polar low activity. A weakening of atmospheric troughs causes fewer cold air outbreaks, therefore reducing the number of mesocyclones (Carleton 1996).

Harold et al. (1999) studied polar lows over the North Atlantic and Nordic Sea region. One facet of their study focused on the influence of the North Atlantic Oscillation (NAO) on polar low frequency and size types. The results indicated a positive correlation (0.429) between mid-size polar lows (200 to 600 km) and positive NAO events. Harold et al. (1999) hypothesized that the reason for a positive correlation was because NAO events force cold air over the central Nordic Seas, providing an opportunity for air-sea instability and polar low development. In addition, polar low frequency was influenced by the strength of the circumpolar circulation (circumpolar vortex) which was unrelated to the NAO process. The results showed a significant negative correlation (-0.957) between an enhanced circumpolar vortex and mid-size polar lows. The average correlation for all polar lows of different sizes (<200 to 1000 kilometers) was smaller (-0.611). Meteorologically, this means polar low genesis is high when the pressure is high over the polar regions and the circumpolar vortex is weak.

The Pacific Ocean basin is primarily influenced by climatic oscillation pattern changes that are related to the El Nino Southern Oscillation (ENSO), Arctic Oscillation, Aleutian Low and the Pacific Decadal Oscillation (PDO). Because these climatic oscillations have the greatest meteorological influence on large-scale pattern changes and synoptic events, it is reasonable to assume they would influence polar low frequency. In fact, Anthes (1986) hypothesized mesoscale events may be dominated by large scale processes at various places at different times. Therefore, it is reasonable to hypothesize that polar lows are influenced by large scale changes in the atmosphere and/or ocean. Six different indices are investigated with the polar lows: the Pacific Decadal Oscillation Index (PDOI), Aleutian Low Pressure Index (ALPI), Atmospheric Forcing Index (AFI), Multivariate ENSO Index (MEI), Pacific-North America Index (PNAI) and the Arctic Oscillation Index (AOI).

2.0 Data

First, polar lows are selected from satellite imagery for the study. Geostationary Operational Earth Satellite, (GOES) imagery was obtained from the National Climatic Data Center's (NCDC) Historical GOES Browse Server located on the internet (NCDC 2001) and the National Oceanographic and Atmospheric Admistration (NOAA) Advanced Very High Resolution Radiometer (AVHRR) channel 4 (10.4-11.55 μm) and High Resolution Picture Transmission (HRPT) imagery was obtained by NOAA's Satellite Active Archive (SAA) to determine cloud types and any other mesoscale features associated with polar lows.

A satellite imagery review was conducted to detect polar lows. Initially, GOES infrared (IR) imagery was utilized to locate areas of polar lows. Images starting from late 1992 to 1995 were in "full disk" view, because only one satellite was operational. The resolution was poor for detecting small polar lows (< 400 km); yet, useful for detecting larger polar lows (400-1000 km). This introduces an inherent bias in the study, because mid-size to large polar lows are preferentially recorded. However, polar lows recorded in the North Atlantic and Nordic Seas were mostly in the mid-size (400-800 km) range (Harold et al. 1999). Therefore, for this study, it is reasonable to assume that the majority of the polar lows were recorded. The best-case criteria for this study of polar lows include the following objective thresholds:

1. Both comma and spiraliform polar lows are mesoscale (<1000km) and independent of any large-scale synoptic features in the satellite imagery.

2. The polar lows must lie north of a notable frontal boundary feature or polar front via the 500 hPA Reanalysis fields. The 5400 m contour is a rough approximation of the position of the polar front which is similar to the Yarnal and Henderson (1989) criterion.

3. Geographically the polar lows lie within the domain of study, as shown in Fig. 1.1.

4. Polar lows are selected for the months of November through March.

Satellite coverage over the eastern Pacific Ocean improved after 1996 because a new satellite was positioned over the Pacific Ocean region. Better resolution from the new GOES satellite increased the ability to discern small-scale systems over the area of interest. Over 3600 GOES images were analyzed for polar lows from November through March, starting in 1992 and continuing through the year 2000.

3.0 Methodology

A statistical analysis is performed on the polar lows over the region of interest. The time frame includes the winter seasons between 1992 and 2000. The statistical analysis includes correlations between polar low frequency and the various indices related to atmospheric and oceanographic changes.

Index values were averaged for each winter period under investigation (Table 1.0). Time series, main effects plot, regression, residual and correlation analysis were conducted between the number of polar lows recorded and each average index value for the winter season.

Table 1.0

Polar Low Numbers and Mean Index Values for the Corresponding Winter Period

Year	# Polar Lows	PDOI	ALPI	AFI	MEI	PNAI	AOI
92-93	19	0.492	-1.100	-0.130	0.789	0.400	1.750
93-94	21	0.982	-0.640	0.370	0.318	-0.040	0.477
94-95	13	-0.606	1.520	-0.340	0.986	0.100	1.109
95-96	20	0.446	0.800	0.350	-0.505	-0.240	-0.603
96-97	17	0.244	0.540	0.020	-0.370	-0.440	0.504
97-98	52	1.238	4.710	1.530	2.519	1.020	-0.181
98-99	30	-0.454	0.010	-0.100	-0.961	-0.020	-0.023
99-00	9	-1.244	0.150	-0.200	-1.089	-0.180	0.954

To determine the significance of the data and correlations, the C-p statistic and the Durbin-Watson statistic are used. The C-p statistic is:

$$C\text{-}p = (SSEp / MSEm) - (n-2p) \qquad (1)$$

Where:

SSEp = Sum of the Square Error for the best model with p parameters

MSEm = Mean Square Error for the model with all m (model) predictors.

p = the number of parameters in the model

n = the number in the sample

If the model is adequate (i.e., fits the data well), then the expected value of C-p is approximately equal to p, the number of parameters in the model. A small value of C-p indicates that the model is relatively precise (has small variance) in estimating the true regression coefficients and predicting future responses. This precision does not improve significantly by adding more predictors. Models with considerable lack of fit have values of C-p larger than p.

The Durbin-Watson statistic looks for autocorrelation in the residuals based upon their sequential order. If the data are recorded over time, this statistic could detect time trends which, if accounted for, could improve the fitted model. As a rule of thumb, when the Durbin-Watson statistics falls below 1.4 or 1.5, one should plot the residuals versus row number to see if there is any noticeable correlation between residuals close together in time. For a perfectly random sequence, the Durbin-Watson statistic would equal 2.0. A Durbin-Watson statistic (D-Ws) far from 2.0 (e.g., < 1.5 or > 2.5) indicates violation of the assumption that the errors are uncorrelated.

The formula for the Durbin-Watson statistic is as follows:

$$d = \frac{\sum_{t=2}^{n}(e_t - e_{t-1})^2}{\sum_{t=1}^{n}(e^2)} \qquad (2)$$

Where:

d = Durbin-Watson statistic

t = time period counter

e = residual ($Y_i - Y_e$)

n = number in the sample

4.0 Results

4.1 Time Series and Main Effects

The number of polar lows (PLs) was less than 30 up to the 1996-1997 winter season with small fluctuations (Fig. 2.0). The largest number (52) occurred during the 1997-1998 winter season. Even more interesting was the rapid decrease in polar low numbers (9) during the 1999-2000 winter season when the PDO transitioned into its cool phase along western North America.

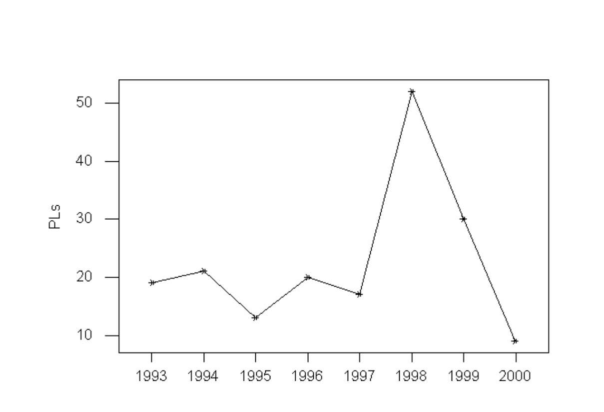

Fig. 2.0. Time Series of the number of polar lows for each winter season. The y axis represents the number of polar lows per winter season. The x axis represents the ending year of the winter season (e.g. 1993 = 1992-1993 winter season).

In addition, nearly all the index values (PDOI, ALPI, AFI, MEI, and the PNAI) revealed some similarity to the frequency of polar lows. The PDOI, ALPI, AFI, MEI, and the PNAI index values increased during the 1997-1998 winter season, which coincided with the increase in polar lows (Fig. 3.0). The exception was the AOI which had lower values and no large increase in fluctuations over the 1997-1998 winter season (Fig 3.0f). In fact, the AOI had large values in the beginning of the study period coinciding with steady or decreased numbers of polar lows.

To compare polar low frequency and average winter numbers with all six atmospheric/oceanographic indices, a main effects plot was generated (Fig. 4.0). Again, the PDOI, ALPI, AFI, MEI and PNAI revealed similar patterns to each other with regard to high index values and higher polar low frequency. The AOI had a nearly reversed situation when compared with the other five indices, with higher polar low numbers associated with negative AOI index values.

4.2 Regression and Residual Analysis

Interesting relationships between the polar low frequency and index values were revealed by regression and residual analysis. The linear regressions of PDOI, ALPI, AFI, MEI and PNAI all showed positive slopes while AOI had a negative slope (Fig. 5.0). The linear regressions suggested that the index values are good predictors of polar low frequency over the North Pacific Ocean

The R^2 adjusted value was less than 0.50 for PDOI, ALPI and MEI indicating the strength of the regression between PDOI, ALPI and MEI and polar low frequency was small. The R-value is the proportion of variability in the y variable while R^2 (adjusted) is R adjusted for degrees of freedom. If a variable is added to an equation, R will get larger even if the added variable is of no real value. R^2 adjusted is an approximately unbiased estimate of the population R. It helps determine the strength of the regression analysis.

The R^2 adjusted value for AFI and PNAI were above 0.50 with considerable less Sum of Squares (SS) error suggesting the linear regression was strong. Polar lows were more frequent during positive AFI and PNAI because the atmospheric and oceanographic conditions favored genesis. These included:

1. Deep and intense Aleutian Low
2. Upper long-wave trough over the central and east central Pacific
3. Warmer waters near western North America and parts of the Gulf of Alaska
4. Increased cold air advection over the warmer ocean that resulted in frequent release of sensible and latent heat into the boundary layer.
5. Convective instability

a.

b.

c.

d.

e.

f.

Fig. 3.0. Time Series of various selected indices for the winter seasons. The y axis represents the index values. The x axis represents the ending year of the winter season (e.g. 1993 = 19992-1993 winter season).
(a) PDOI (b) ALPI (c) AFI (d) MEI (e) PNAI (f) AOI.

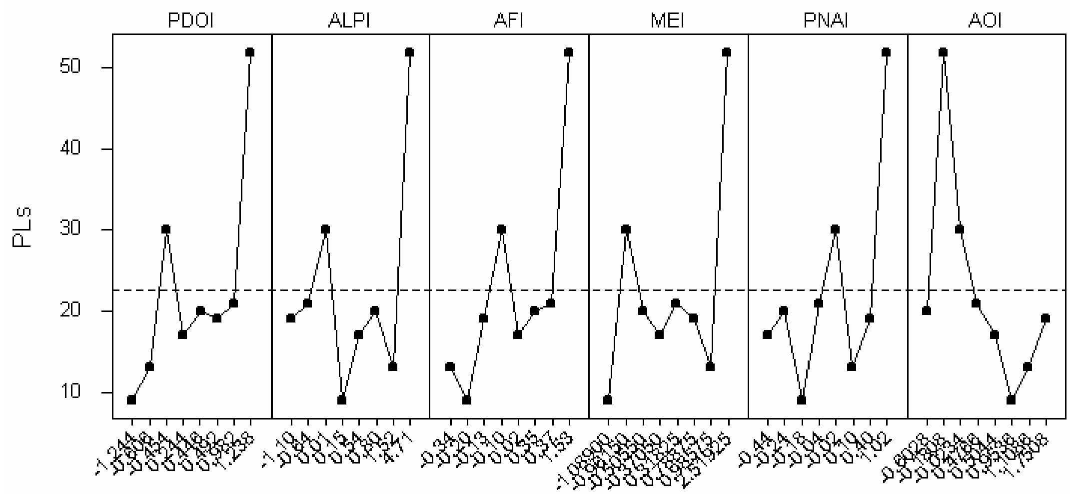

Fig. 4.0. Main Effects Plot: polar low frequency compared to selected indices. The dash line represents the average number of polar lows per winter season.

The polar lows (PLs) versus AOI regression line had a negative slope with a R^2 adjusted value of 0.15 with a large SS error, which suggested that the strength of the regression analysis was weak. During positive AOI, cold outbreaks are infrequent and it suppresses diabatic heating and instability which are needed as a growth mechanism by polar lows.

The normal plot of residuals (not shown) is nearly linear for PLs versus all indexes. The points should generally form a straight line if the residuals are normally distributed. The normal residual plot for PLs vs. PDOI was less linear compared with the other normal residual plots.

The residuals versus fits plot (not shown) should show a random pattern of residuals on both sides of zero. There should not be any recognizable patterns in the residual plot graphs. At first glance, it appeared that the residuals are dispersed randomly. However, the PLs vs. PDOI showed a preponderance of negative values, especially as the fitted values increased.

To measure the association between PLs and indices, Pearson correlations were performed (Table 2.0). PLs develop in regions of low level instability. Positive AFI environmental conditions provide the release of sensible and latent heat, convective instability and initial disturbed weather. The highest correlation was between PLs and AFI at 0.877. The results was in good agreement with known environmental conditions needed for polar low formation, for the AFI represented warm SSTs, a strong Aleutian Low and deep long-wave patterns (cold-air advection over water).

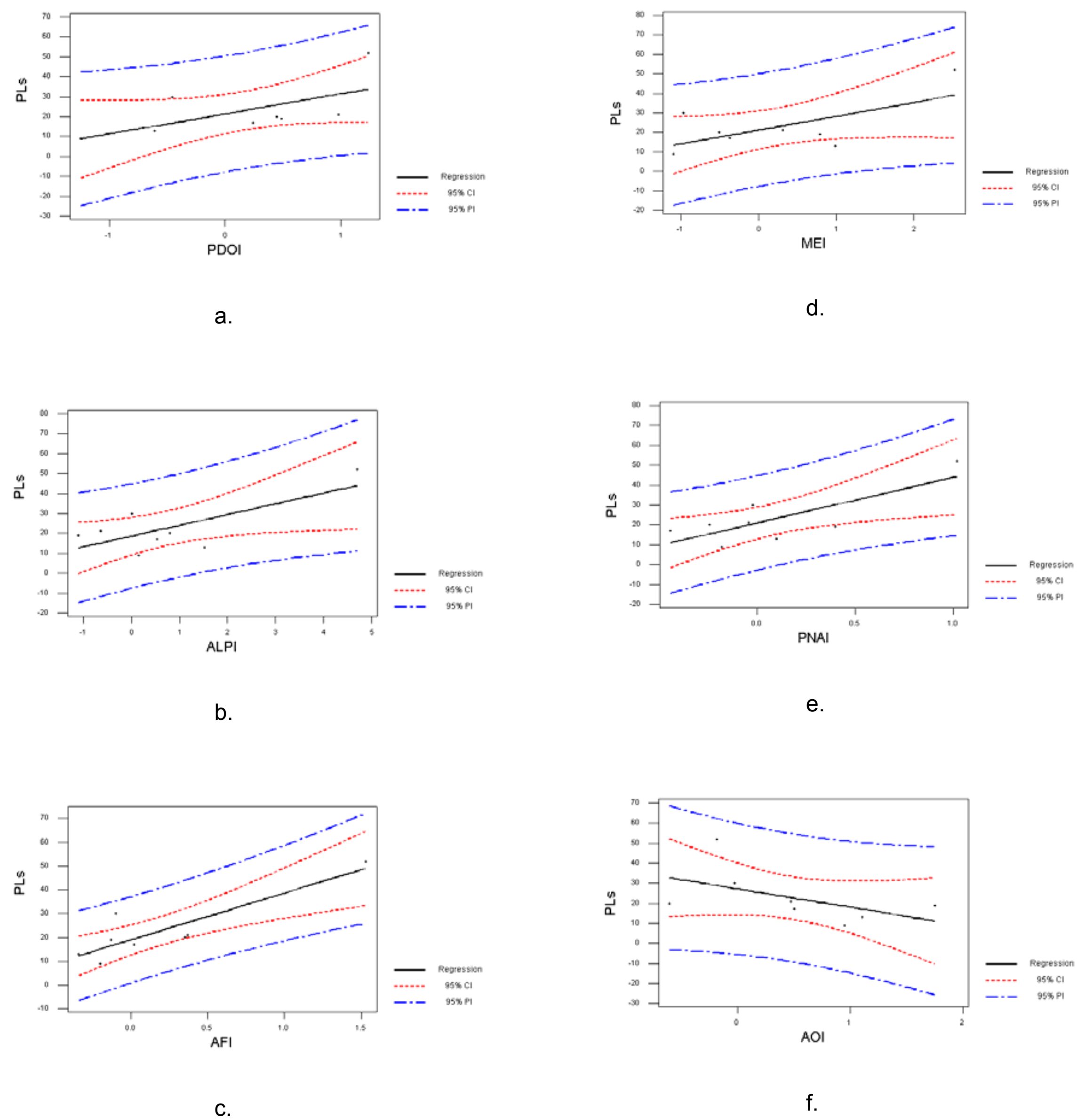

Fig. 5.0. Linear regression between polar low frequency and atmospheric/oceanographic index values. Black line: regression. Red dash line: confidence interval. Blue dash line: Predictor interval. (a) PDOI (b) ALPI (c) AFI (d) MEI (e) PNAI (f) AOI.

It was interesting to note the high correlation between MEI and PNAI at 0.870. This occurred, because there are strong relationships between positive ENSO events and the positive PNA long-wave patterns, as well as, La Nina and reverse (negative) PNA events.

Further, the MEI was overshadowed by the PNA pattern that ENSO helped produce. Warm SSTs which were associated with the PDO and ENSO, played a role in polar low genesis, but SSTs were not an exclusive factor in determining polar low frequency.

Moderately strong correlations existed between PLs and the indices of ALPI (0.724) and PNAI (0.775). The lowest positive correlations were between PLs and the indices of PDOI (0.633) and MEI (0.641). The higher positive correlations indicated that polar low frequency was again influenced by the strength of the Aleutian Low and long-wave patterns over the region.

A negative correlation (-0.524) existed between PLs and the Arctic Oscillation Index values. As suggested earlier, a positive AOI suppressed polar low development, because the circumpolar vortex was spinning faster and did not allow cold air to spill over the warmer ocean. Conversely, this implied that negative AOI indicated cold air outbreaks over the water which may have helped spawn polar lows. A negative correlation was similar to the findings of Harold et al. (1999).

4.3 Best Subset Regression

Best subset regression identifies the best fitting regression models that can be constructed with the predictor variables that are specified. By default, all possible subsets of the predictors are evaluated, beginning with all models containing one predictor, and then all models containing two predictors, and so on. The two best models that can be constructed for each number of predictors; in this case the best atmospheric-oceanographic indices that predict polar low frequency. The models are evaluated based on R. The best subset regression is an efficient way to identify models with as few predictors as possible. Subset models may actually estimate the regression coefficients and predict future responses with smaller variance than the full model using all of the predictors. The best single variable as a predictor of polar lows as AFI (R^2 adjusted value = 0.731). The C-p statistic was -0.1. The Durbin-Watson (D-W) statistic is 2.22 (Table 3.0). The AFI represented not only the strength of the Aleutian Low, but the changes in SST in the North Pacific Ocean and the strong westerly winds.

The best two variable regression model utilizes PNAI + AOI. The R^2 adjusted value is 0.856. The best subset value was a surprising result, for the strength of the regression was weak for the regression between PLs and the AOI values by themselves. However this suggests that during positive PNAI events the upper long-wave trough dominates the central and east central North Pacific Ocean region. Very cold air aloft and a warm, moist layer at lower levels produce unstable lapse rates that lead to convective instability. The upper levels are also influenced by negative AOI events. Besides cold air outbreaks over an already unstable region, filaments of positive potential vorticity (PV) are able to move equatorward because they are no longer impeded by a strong circumpolar vortex.

Also, the combination of the two variables produced less random errors and a better measure of predictability. This suggested that the upper level atmospheric long wave pattern over the North Pacific Ocean and its association with a weaker Arctic Oscillation (increased cold air surges over the ocean) helped spawn polar lows. Note, that the next best two variable model, AFI + PNAI, represents a upper level atmospheric pattern of the PNA and the low level changes in the boundary layer (instability) helped contribute to an increased polar low frequency.

The best three variable regression models was the PDOI + PNAI + AOI combination. The R^2 adjusted value was 0.837. The C-p statistic was higher than previous models (1.60). Yet the D-W was nearly perfect at 2.07. The added parameter acted as a correlation “surplus”, re-enforcing the other two parameters. The combination suggested upper level atmospheric patterns of the PNA (pronounced upper air long wave pattern) that are associated with a negative AOI (increased cold air outbreaks and upper air forcing via PV) and above normal warm SSTs helped produce polar lows over the North Pacific Ocean.

The other best three variable regression model, AFI + PNAI + AOI, has nearly identical statistics to the first three variable regression models, except for the D-W was much higher (2.32). The best 4 variable regression model consisted of PDOI + MEI + PNAI + AOI. This regression model has a low D-W value of 2.34. The R^2 adjusted value was high (0.80). The C-p statistic was also high (3.50). The MEI and PNAI re-enforced one another in the equation, but PDOI and AOI also aided in the prediction of PLs, because of cold air outbreaks and/or upper level forcing occurring over warmer (unstable boundary layer) waters.

5.0 Summary

Although the study is for eight winter periods, the results of the analyses suggest that there is a relationship between polar low frequency and large scale atmospheric/oceanographic changes over the Gulf of Alaska region. The AFI was strongly linked to polar low frequency. The high correlation between polar low numbers and the AFI makes scientific sense when thinking about the optimum conditions for polar low development. Positive values of AFI represent an intense Aleutian Low, above average frequency of westerly winds, cooling of sea surface temperatures in the central North Pacific and warm SSTs within North American coastal waters and parts of the Gulf of Alaska. Polar low development occurs behind the polar front and in the vicinity of old upper level lows or troughs. The energy to produce polar lows was aided by cold air advection over the warm waters (latent and sensible heat release).

There is a moderately strong correlation/positive linear relationship between polar lows and ALPI and PNAI. The ALPI can be viewed as a subset of AFI. It is the measure of the intensity of the Aleutian Low, for a higher index value represents a period of instability. The PNAI can be viewed as the position of long-wave patterns (trough over the Central or east Central Pacific Ocean). Within the regions of troughs, there is very cold air aloft and a warm, moist layer at lower levels that produces unstable lapse rates that lead to convective instability. It is related to positive ENSO events. However, MEI did not correlate strongly with polar low frequency in the winter season. It was possible the MEI was masked by the PNA pattern which helped create.

There was a negative correlation between polar low frequency and positive AOI values, because a positive AOI represents cold arctic air locked over the source region, unable to penetrate over the warmer waters. Negative AOI values implied arctic air over warmer oceanic waters was present. This encouraged polar low genesis. The release of latent and sensible heat aided in its development by the passing of an arctic air mass over the warmer seawater. In addition, the flaccid circumpolar vortex allows filaments of positive PV to move southward over areas of low level instability. The movement of the upper level forcings, represented as positive PV, encourages vortex growth near the surface. Nevertheless, these findings are similar to Harold et al.’s (1999) study, which showed polar low frequency was related to the strength of the circumpolar vortex.

A best subset regression analysis was performed with all the atmospheric/oceanographic indices. The best subset regression analysis output suggested AFI as the single best predictor just as the linear regression demonstrated. The combinations of PNAI, AOI, PDOI and AFI indicated that polar low frequency was a function of very cold outbreaks (negative AOI values) over the Northern Hemisphere warmer waters. An intense Aleutian low combined with proper long-wave pattern aided by cold air advection over warmer waters (positive PDO) might help predict polar low numbers in the winter. This research can serve as the foundation for future polar low investigations. The climatic indices are the basis for the development of a polar low index that someday may identify conditions and times of polar low outbreaks.

7.0 REFERENCES

Anthes, R. A. 1986: The general question of predictability. Mesoscale Meteorology and Forecasting. American Meteorological Society, Boston MA. 636-656.
.
Barry, R. G. and A.M. Carleton. 2001: Synoptic and Dynamic Climatology. Routledge, New York, NY. 620p.

Bromwich, D.H. A Case Study of Mesoscale Cyclogenesis over the Southwestern Ross Sea. Antarctica Journal of US 1987; Vol. 22, 254-256.

Businger, S. 1985: The synoptic climatology of polar low outbreaks Tellus, Vol. 37A, 419-432.

Businger, S. 1987: The synoptic climatology of polar low outbreaks over the Gulf of Alaska and Bering Sea. Tellus, Vol. 39, 307-325.

Carleton, A.M. 1996: Satellite Climatological Aspects of Cold Air Mesocyclones in the Arctic and Antarctic. The Global Atmosphere and Ocean System, Vol. 5, 1-42.

Carleton, A.M. and D. A. Carpenter. 1990: Satellite climatology of a “polar lows” and broadscale climatic associations for the southern hemisphere. International Journal of Climatology, Vol. 10, 219-246.

Department of Fisheries and Oceans of Canada, Pacific Region 2002: http://www.pac.dfompo.gc.ca/pages/default_e.htm

Deser, C. and M.L. Blackmon, 1995. On the relationship between tropical and North Pacific sea surface temperature variations. Journal of Climate, Vol. 8, 1677-1680.

Deser, C., M.A. Alexander and M.S. Timlin, 1996: Upper-ocean thermal variations in the North Pacific during 1970-1991. Journal of Climate, Vol. 9, 1840 -1855.

Forbes G. S. and W.D. Lottes 1985. Classification of mesoscale vortices in polar airstreams and the influence of the large-scale environment on their evolutions. Tellus, Vol. 37A, 132-155.

Harley, D.G. 1960. Frontal Contour Analysis of a “Polar Low”. Meteorological Magazine, Vol. 89 146-147.

Harold, J. M., G.R.Bigg and J. Turner. 1999. Mesocyclone activity over the Atlantic. Part 2: An Investigation of Causal Mechanisms. International Journal of Climatology, Vol. 19, 1283-1299.

Harold, T. W. and K.A. Browning. 1969. The polar low as a baroclinic disturbance. Quarterly Journal of the Royal Meteorological Society, Vol. 95, 710-723.

Horel, J. D. and J. M. Wallace. 1981. Planetary Scale Atmospheric Associated with the Southern Oscillation. Monthly Weather Review, Vol. 863-878.

Johannessen, O.M. 1987. Summer Marginal Ice Zone Experiments During 1983 and 1984 in Fram Strait and the Greenland Sea. Journal of Geophysical Res., Vol. 92. 6716-6718.

Leathers, D.J., B. Yarnal and M. A. Palecki. 1991. The Pacific/North American Teleconnection Pattern and the United States Climate Part I. Journal of Climate, Vol. 4, 517-528.

Leider, M. and G. Heinemann. 1999. A Summertime Antarctic meoscyclone event over the Southern Pacific during FROST SOP-3: A mesoscale analysis using AVHRR, SSM/I, ERS and Numerical Model Data. Vol. 14, 893-908.

Locatelli, J.D., P.V. Hobbs and J.A. Werth. 1982. Mesoscale Structures of Vortices in Polar Air Streams. Monthly Weather Review, Vol. 110, 1417-1433.

Mantua, N. J., S. R. Hare, Y. Zhang, J. M. Wallace and R. C. Fancis. 1997. A Pacific Interdecadal Climate Oscillation with Impacts on Salmon Production. Bulletin of the American Meteorological Society, Vol. 78, 1069-1079.

McFarlane, G.A., J. R King and R. J. Beamish. 2000. Have there been recent changes in climate? Ask the fish. Progress in Oceanography, Vol. 47, 147-169.

Minobe, S., 1997: A 50-70-year climatic oscillation over the North Pacific and North America. Geophysical Research. Letters, Vol. 24, 683-686.

Minobe, S. 2002: http://tao.atmos.washington.edu/pdo/
National Center for Atmosphere Research (NCAR) 2002: http://www.ncar.ucar.edu/ncar/

National Climatic Data Center (NCDC) 2001: Historical GOES Browse Server.http://www5.ncdc.noaa.gov:7777/plwebapps/plsql/goesbrowser.goesbrowsemain.

Pedgley, D.E. A Mesoscale Snow System. Weather 1968; Vol. 23, 469-476.

Reed, R.J. Cyclogenesis In Polar Air Streams. Monthly Weather Review 1979; Vol. 107, 38-52.

Reed, R.J., and W. Blier. 1986a. A Case Study of Comma Cloud Development in the Eastern Pacific. Monthly Weather Review, Vol. 114, 1681-1695

Reed, R.J., and W. Blier. 1986b A Further Study of Comma Cloud Development in the Eastern Pacific. Monthly Weather Review, Vol. 114, 1696-1708

Thompson, D. W. J, and J. M. Wallace, 1998. The Arctic Oscillation signature in the wintertime geopotential height and temperature fields. Geophysical. Research Letters, Vol. 25, 1297-1300.

Thompson, D. W. J. 2001: http://jisao.washington.edu/data/aots/

Turner, J., and D. Warren. The Structure of Subsynoptic-Scale Vortices In Polar Air-Streams From AVHRR and TOVS Data. Second Conference on Polar and Meteorology and Oceanography, AMS, Boston, MA, 1988.

Twitchell, P. F., E. A. Rasmussen and K. L. Davidson. Polar and Arctic Lows. Hampton, Virginia: A. Deepak Publishing; 1989.

Wallace, J. M., and D. S. Gutzler, 1981. Teleconnections in the geopotential height field during the Northern Hemisphere Winter. Monthly Weather Review, Vol. 109**,** 784-812

Wilhelmsen, K 1985: Climatological study of gale-producing polar lows near Norway. Tellus Vol. 37A, 451-459.

Wilks, Daniel S. 1995: Statistical Methods in Atmospheric Sciences. Academic Press, San Diego, CA. 467p.

Wolter, K., 1987. The Southern Oscillation in surface circulation and climate over the tropical Atlantic, Eastern Pacific, and Indian Oceans as captured by cluster analysis. Journal of Climate and Applied Meteorology, Vol. 26, 540-558.

Wolter, K., and M.S. Timlin, 1993. Monitoring ENSO in COADS with a seasonally adjusted principal component index. Proceedings of the 17th Climate Diagnostics Workshop, Norman, OK, NOAA/N MC/CAC, NSSL,Oklahoma Climatological Survey, CIMMS and the School of Meteorology, Univ. of Oklahoma, 52-57.

Xie S. -P. 2001. Pacific Decadal Variability: Patterns and processes. University of Hawaii, iprc.soest.hawaii.edu/~xie/pdo.doc

Yarnal, B. and K. G. Henderson. 1989. A Satellite-Derived Climatology of Polar-Low Evolution in the North Pacific. International Journal of Climatology, Vol. 9, 551-566.

Table 2.0

Pearson Correlations between polar lows (PLs) and selected indices

	PLs	PDOI	ALPI	AFI	MEI	PNAI
PDOI	0.633					
ALPI	0.724	0.304				
AFI	0.877	0.751	0.763			
MEI	0.641	0.628	0.676	0.663		
PNAI	0.775	0.483	0.635	0.678	0.870	
AOI	-0.524	-0.318	-0.463	-0.575	0.060	.025

Table 3.0

Best Subsets Regression between polar lows (PLs) and selected indices

Subset Number	Group	R^2	R^2 (adj)	C-p	S	D-Ws
1	AFI	76.9	73.1	-0.1	6.9349	2.22*
1	PNAI	60.1	53.5	2.8	9.1125	1.60
2	PNAI + AOI	89.7	85.6	-0.2	5.0710	2.20*
2	AFI + PNAI	83.0	76.1	0.9	6.5279	2.26*
3	PDOI + PNAI +AOI	90.7	83.7	1.6	5.4010	2.07*
3	AFI + PNAI + AOI	90.2	82.8	1.7	5.5470	2.32
4	PDOI + ALPI + MEI + PNAI	92.3	82.1	3.3	5.6562	2.77
4	PDOI + MEI + PNAI + AOI	91.4	80.0	3.5	5.9709	2.34

Note: * signifies best values and errors that are uncorrelated.