THE NATURE OF SNOW AND RAIN ALONG THE NORTHERN GULF OF ALASKA DURING THE WINTER MONTHS

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ABSTRACT

This study looks at the synoptic setting for heavy snow events that occur along the Gulf of Alaska coastline from Prince William Sound eastward to Yakutat Bay. Specifically, air temperature, wind speed and wind direction at several atmospheric levels is examined. By using some of the largest snowstorms in the history of Valdez as input data, a composite idealized snowstorm is constructed that helps weather forecasters focus on the most essential characteristics of these events.

Using monthly and seasonal snowfall data and supplemented by rain data at several locations along the North Gulf coast, we investigate the possible linkage between the phases of El Nino & Southern Oscillation and observed amounts of snow and rain. Correlations with additional climate drivers and teleconnection indices are also discussed. Results indicate that snowfall along the North Gulf Coast is a function of both air temperatures and the frequency in which storms move across the region. Inland where winter air temperatures remain below freezing during the winter months, snowfall is controlled almost exclusively by storm frequency. Unfortunately, there is no clear-cut correlation between the various climate drivers and snow/rain in the area of interest. Currently, the best that we can do is present seasonal snow forecast as generalized probabilities. (KEYWORDS: teleconnections, sea surface temperatures, Gulf of Alaska, snowfall, storm frequency).

INTRODUCTION

Snowfall along the northern Gulf of Alaska (GOA) is highly variable in space and time in part due to the mountains terrain and the resulting impact that the movement of air over the mountains has on atmospheric dynamics; and secondly due to the fact that the surface air temperatures at sea-level stations frequently cross the freezing threshold during the winter months (November-March). Large seasonal snowfalls have been documented not only at Valdez and adjacent Thompson Pass, but at Alyeska Resort in Girdwood as well. No one has studied snowfall across this region in detail, although in a related study Papineau (2001) analyzed the correlation between winter surface air temperatures at several stations in the area of interest with El Nino & Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO). Before analyzing the *climatology* of snowfall, an understanding of the main synoptic patterns that produce large snow *events* at these locations will reveal the fundamental parameters that control the production of snow in the atmosphere.

CHARACTERISTICS OF HEAVY SNOW EVENTS

Table 1 shows the daily snowfall and precipitation at Valdez for five large multi-day events that have occurred in the last several decades. The main point of interest is that the snow to water ratio typically ranges from 1:25 to 1:17- indicating that snow is moderately wet. In other words a substantial amount of water is transported onshore in these events. Other stations such as Cordova and Yakutat tend to experience mixed snow and rain events with ratios closer to 1:10. Analysis of a series of heavy snow events across the geographic areas in question reveals the following characteristics:

1. The preferred 700 mb wind direction (steering winds) is SSE-SSW that is from $150^o – 230^o$. This indicates that moisture is being transported northwards from the persistent baroclinic zone (storm track) over the central North Pacific. Although these plumes of moisture do not meet the definition of atmospheric rivers as per mid-latitude guidelines, they are essentially their high latitude cousins. The local terrain dictates the preferred wind direction, for example, at Alyeska Resort SE to S flow produces the largest snowfalls; while SW flow is drier because this trajectory intersects upstream terrain which depletes the moisture before it reaches Alyeska.

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Table 1. Valdez historical heavy snowfall (cm) events

Month/Year	Day	Snow (cm)	Precip (cm)	Ratio
Jan 2012	5	48.8	2.87	1:17
	6	49.0	4.52	1:11
	total	97.8	7.39	1:13
Dec 2009	14	20.5	0.76	1:27
	15	98.3	5.18	1:18
	16	54.3	3.47	1:17
	17	22.3	1.37	1:17
	total	195.6	10.8	1:17
Jan 2004	9	76.2	2.79	1:26
	10	36.0	1.62	1:22
	total	112.3	4.41	1:25
Dec 2002	30	80.5	2.79	1:29
	31	50.0	2.48	1:20
	total	130.5	5.28	1:25
Feb 1996	4	75.2	3.53	1:21
	5	77.9	4.31	1:17
	6	36.3	4.08	1:9
	total	192	11.94	1:16

2. Wind speeds at 700 mb typically range from 15-25 ms^{-1} indicating the presence of a low-level jet (LLJ). Strong and persistent winds do two important things: they transport copious amounts of moisture onshore, and secondly, interact with the terrain producing strong vertical motion.

3. Barrier jets are typically present along the coastal margin. Their role in the production of snow in the atmosphere is not well understood at this time, although they may enhance upstream lifting of air (850mb-700mb) as it moves onshore.

4. Air temperatures tend to increase during heavy snow events. Also note that the snow to water ratios typically increase for multi-day events. The presence of a LLJ and warming trends indicates the presence of the warm sector of an extratropical cycle. These features are clearly evident when these events are studied using any reanalysis data set.

5. Heavy snow events may be associated with frontal passage but it is not a necessary requirement.

6. The most common synoptic weather pattern is a ridge of high pressure located over western Canada with a low/trough to the west over the western GOA. This pattern can persist for a number of days.

7. Heavy snow events are less frequent at Yakutat and in the Panhandle when compared to the North Gulf Coast.

SNOW CLIMATOLOGY

A comparison of seasonal snowfall at Valdez and Yakutat as seen in Figure 1 indicates that there is no trend at Valdez although it only has a 36 year history, while Yakutat clear shows a larger mean prior to 1977. Inspection of the number of snow days at Yakutat, that is days in which at least .25 cm of snow was observed, indicates that the number of snow days has decreased by 10% to 15% since 1977 while the number of precipitation days (precip days), that is days where at least 0.025 cm of water equivalent is measured, has increased by 5% to 10%. 1977 corresponds to the well documented climate shift in the North Pacific (Namias, 1978; Bond et al., 2003).

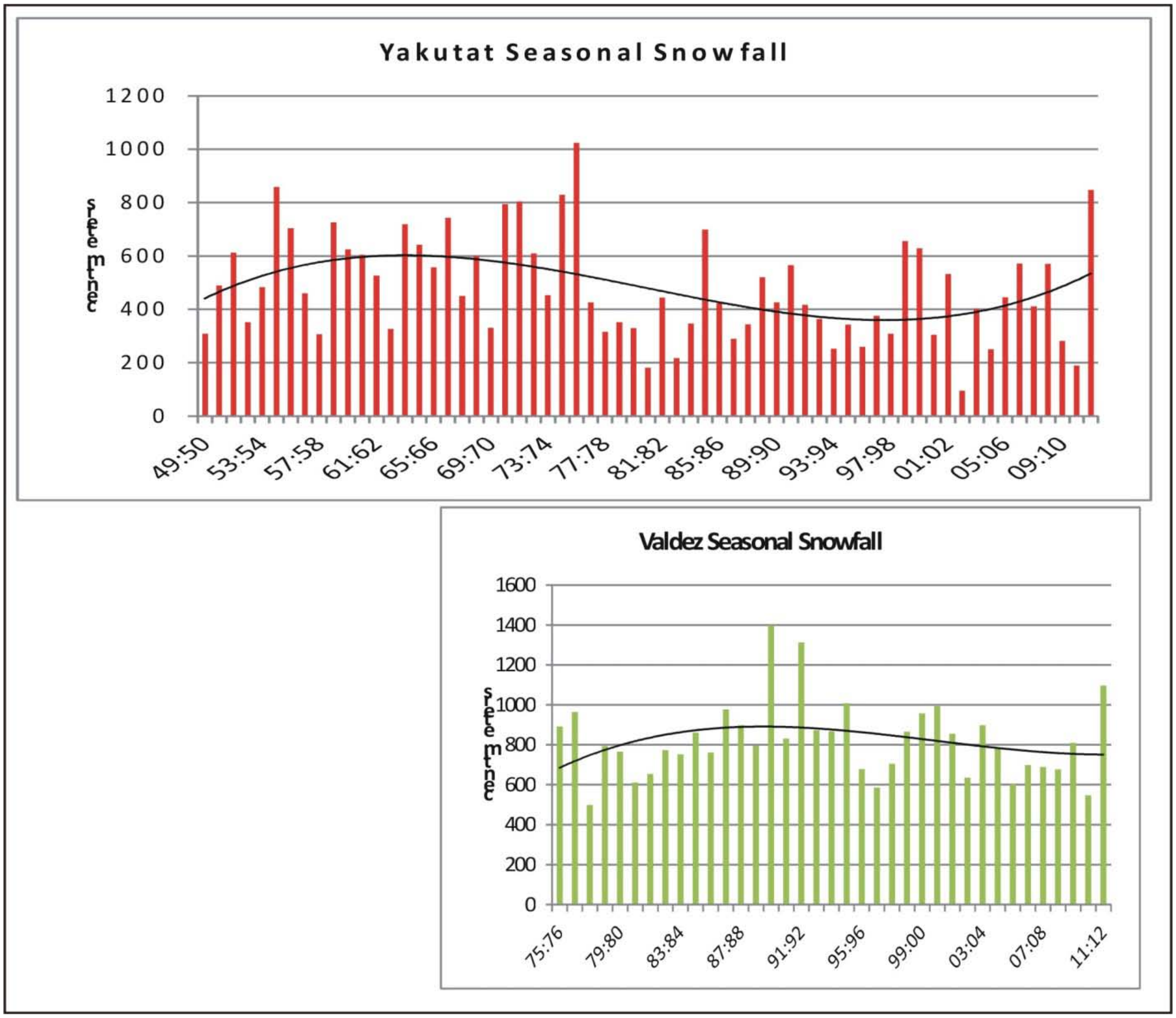

Figure 1. Seasonal snowfall (cm) at Yakutat and Valdez

Analysis of snow days, snowfall, and precip days indicates that there is a high correlation between seasonal snowfall and snow days at Yakutat, indicative of the fact that 6.5 cm of snow is produced for each snow day. This is not true of precipitation versus precip days, where many days with light rain increase the total of precip days without adding to the accumulated winter total. This would seem to indicate that the dynamic forcing on snow days is significantly larger than on many rainy days where light rain or drizzle skews the data. Table 2 shows the ten snowiest winters at Valdez, while Table 3 shows the ten snowiest winters at Yakutat.

It is apparent at Valdez that there is a slight tendency for El Nino's to be more frequent than La Niña's (5 to 3). The other teleconnection indices show a mix of values, in other words, the correlation between any given index and heavy snowfall is weak or non-existent.

Table 3, however, shows that at Yakutat years with heavy snowfalls tend to favor La Nina winters over El Nino winters (7 to 2). In addition, a number of the teleconnection indices also indicate modest correlation (see Appendix for summary of teleconnection indices). For example, when the Pacific Decadal Oscillation (PDO) is negative, the Alaska Index is negative and the North Pacific Index is large, there is a tendency for heavy snow at Yakutat. When the Aleutian Low is weaker than normal, the GOA region tends to experience a higher frequency of west-to-northwesterly winds, which in turn generate cooler than normal air temperatures.

Table 2. Valdez seasonal snowfall (cm) compared with various seasonal parameters and teleconnection indices. GOA SST's are Nov-Mar anomalies based on period of record mean.

Year	Snow (cm)	Snow days	ENSO	PDO	AO	GOA SST's	AK Index	NP
89:90	1399	94	N	-0.46	1.4	-0.5	-0.5	10.9
91:92	1313	113	EN+	0.31	0.9	0.1	-1.7	6.5
94:95	1008	86	EN	-0.61	0.9	-0.7	0.4	8.6
00:01	994	110	LN	0.27	-1.4	0.1	0.8	7.1
76:77	963	116	EN	1.19	-1.5	0.6	-0.3	6.0
86:87	977	95	EN+	1.85	-0.7	0.9	-0.2	6.0
99:00	958	99	LN+	-1.24	0.7	-0.6	-0.8	8.4
03:04	898	78	N	0.47	-0.4	0.2	-0.3	8.6
87:88	897	105	EN	1.27	-0.4	0.3	0.1	8.1
75:76	892	80	LN+	-1.53	0.8	-0.7	-1.7	10.1

Table 3. Yakutat seasonal snowfall (cm) compared with various seasonal parameters and teleconnection indices. GOA SST's are Nov-Mar anomalies based on period of record mean.

Year	Snow (cm)	Snow days	ENSO	PDO	AO	GOA SST's	AK Index	NP
75:76	1024	102	LN+	-1.5	0.8	-0.7	-1.7	10.0
54:55	858	86	LN	-0.5	-0.8	0.4	-1.1	11.2
11:12	848	100	LN	-1.5	0.9	na	na	na
74:75	830	89	LN	-0.4	0.4	-0.1	-1.5	10.0
71:72	804	112	LN	-1.8	0.2	-1	-0.6	11.8
70:71	795	112	LN+	-1.4	-0.4	-0.3	-1.5	11.5
66:67	743	84	N	-0.6	0.3	-0.2	-0.3	10.9
58:59	726	78	EN	0.0	0.1	0.7	0.7	10.3
63:64	719	102	EN+	-0.9	-0.5	0.4	-1.4	9.1
55:56	704	93	LN+	-2.7	-0.9	-0.5	-0.6	10.3

Considering the ten least snowy seasons at Yakutat, we find that there is a slight edge toward El Nino conditions (5 to 3) over La Nina. The other indices also show some correlation, the PDO tends to be highly positive, the AO negative while the Alaska Index is also positive. The NP shows mixed characteristics. This is consistent with the fact that warm southerly flow increases across the GOA when the Aleutian Low is deeper than normal but remains centered in its climatological position (around 170^{o}W).

The ten least snowy seasons in Valdez in contrast is only moderately correlated with a positive Alaska Index. The important point to consider is that there is a given amount of interplay between air temperatures and the supply of moisture. Overall, west-to-northwest flow tends to be drier than southerly flow, therefore enhanced southerly flow in the GOA may result in the transport of additional moisture but air temperatures along the coast may be too warm for snow.

Table 4 shows the linear correlations between seasonal snowfall and precipitation versus a number of teleconnection indices. The strongest correlations with snowfall are with the NP and PDO followed by the AK index and Yakutat air temperatures. Interestingly, ENSO is not as highly correlated as a number of other indices- probably in part due to the weak signal during El Nino winters. The values of the indices in Table 3 are for concurrent periods of time and do not allow us to make predictions unless we are able to predict the index value. This is generally not possible with the exception of slowly changing SST based indices like the ENSO, PDO or GOA SST anomalies. Table 5 shows the correlation of monthly snowfall at Yakutat compared to monthly teleconnection indices. Correlations are modest for a number of the indices, but no clear-cut favorite emerges.

Traditionally, ENSO has been used as a predictor for Alaska weather/climate because it is predictable in oceanic models, while atmospheric features (teleconnection patterns) like the PNA and AO are not. Although ENSO does have some moderate correlation with snowfall at certain locations, it does have its limitations. Consider the La Nina winters of 2010-2011 and 2011-2012 which produced a desperate amount of snow across most of the state. Focusing on the north Gulf Coast, all snow observing stations reported below normal or near normal snowfall for the 2010-2011 season (Valdez=216", Yakutat=74"), while 2011-2012 was well above normal (Valdez=433", Yakutat=334"). Analysis of the weather patterns shows that in December 2010, and again in March 2011, the storm track had shifted eastward resulting in drier and cooler conditions compared to normal. In November and December 2011, copious amounts of moisture were transported from the North Pacific into the northern GOA. The net result was well above normal snowfall in the area of interest.

Table 4. Yakutat seasonal snowfall and precipitation correlated with various indices.

Index	Snow	Precip	Years
AK Index	-0.48	-0.02	61
AO	0.18	0.08	62
ENSO	-0.36	0.19	62
NP	0.61	-0.37	62
NPGO	-0.08	0.14	58
PDO	-0.58	0.41	61
PNA	0.03	0.15	62
Sib-AK	0.37	0.14	61
WP	-0.04	0.03	59
GOA SST	-0.40	0.30	61
Yak. Temp	-0.53	0.58	62

Further analysis of additional teleconnection indices shows that the PDO was highly negative during both of these winters. The PNA was -0.44 during the first winter but on the order of +0.30 for the second; furthermore the AO shifted from -0.34 during the first La Nina to +0.89 during the second. The negative AO is indicative of cooler air moving southward across the Bering Sea as it did in 2010-2011; however, this supply of cool air would have been limited in 2011-2012 based on the positive AO. In fact, air temperatures across the GOA were actually cooler during the 2011-2012 season which is not what we would expect based solely on the positive phase of the AO. So why the discrepancy between what we would expect and what occurred? Daily precipitation, snowfall, wind speed, wind direction and air temperature data indicates that during 2010-2011 the storm track was highly variable. For example, 700 mb wind direction over the northern GOA indicates higher variance when compared to 2011-2012. Both seasons tapped into the moisture located over the central North Pacific but in 2011-2012 it was in conjunction with cooler air temperatures; hence the net result was above normal snowfall. Why did cooler air temperatures occur with a positive AO? It may result from the fact that the various teleconnection indices, in this case the AO, do not reflect regional shifts in the storm track. Overall, teleconnection indices reveal moderate correlation with snowfall but one index is not enough to describe the state of the atmosphere. Ultimately the storm track across the central and eastern North Pacific is modulated by a host of factors (forcings) that work synergistically. Unfortunately, at this point in time we do not understand how these interactions work.

Table 5. Monthly snowfall at Yakutat correlated with various indices.

index	correlation
GOA SST	-0.33
NP	0.39
AO	0.25
PDO	-0.41
PNA	-0.36
ONI (adj)	-0.18

Finally, it is worth considering the question of what controls seasonal snowfall across the entire GOA. Analysis of precip days across the region indicates that southeast Alaska (Panhandle) has the highest frequency, which can be used as a surrogate for the persistence/variability of the storm track. Along the North Gulf Coast the frequency of precip days decreases. The coefficient of variability (standard deviation divided by the mean) for seasonal snowfall is smallest in the southern Panhandle (Annette) and generally increases along the North Gulf Coast. This indicates that the variability of precip days is higher in the northern part of the Gulf; by inference the storm track displays higher variability in this area as well. The correlation between seasonal snowfall at coastal stations and their respective seasonal air temperatures is high in the Panhandle and also decreases as we move northwest. *The general conclusion is at or near sea-level, seasonal snowfall in the Panhandle is primarily controlled by the air temperatures, the frequency at which storms move across the area is secondary because the number is relatively constant from one winter to the next.*

Along the North Gulf Coast in contrast snowfall is a function of both air temperatures and frequency of storms. This is evident when we compare the correlations between snow and air temperatures as well as snow and precip days for Valdez to Cordova. Although these two stations are in close proximity they have their own local climate regimes. Snowfall at Cordova has moderate negative correlation with air temperatures while Valdez has no correlation. Valdez on the other hand has a strong positive correlation between snow and the number of precip days, while Cordova has no correlation. Snow at Valdez is controlled by the number of storms (precip days) that move across the region because during the winter air temperatures almost always remain below freezing. At Cordova, in contrast, air temperatures fluctuate above and below freezing during the winter, hence snowfall is a function of both storm frequency and air temperatures. *Inland where winter air temperatures remain below freezing despite the transport of warmer air from the GOA (compare -10^{o}C to -4^{o}C, it will still snow), snowfall is almost exclusively controlled by storm frequency*. Although Mesquita *et al* (2010) did not find any trends in the number of storms that enter the GOA during the 1948-2008 period; we do know that the interannual variability of the of the region is coupled with the trajectory of the storm track. Essentially it is the accumulative history of the storm track over the course of the winter. This was noted by Rodionov *et al* (2007) in their study of the climate of the Bering Sea; where a southeasterly trajectory transports significantly warmer air into the basin than a southwesterly trajectory. The same type of reasoning applies to the GOA. The difficulty with analysis in the Gulf is that southwesterly flow can for example produce a wide assortment of weather patterns; from cool and dry to cool and wet and at times warm and wet. Cooler air is transported from the northern Bering Sea while warm air originates in the mid-latitudes. Hence the positioning of the Aleutian Low and resulting storm track is of vital importance.

CONCLUDING THOUGHTS

1. If the climate community is ever going to understand the atmospheric-oceanic system and its control on snow, precipitation and air temperatures in the GOA region, we need to move away from seasonal and even monthly composites and analysis sub-monthly data because the atmosphere does not work on calendar months. This would limit our ability to correlate with the various teleconnection indices since they are based on monthly data. How to overcome this difficulty is not evident at this point in time.

2. We need to discern between a phase shift of a particular forcing (PDO, ENSO) and a complete shift in a mode. An example of the latter would be the predominance of the PDO for a given period which then is replaced by a completely different forcing. Ultimately, the position and strength of the storm track is a function of a multitude of atmospheric, cyrospheric and oceanic forcings that vary on a multitude of time scales, from weeks to seasons to decades.

3. There are no canonical seasonal weather patterns in the GOA. Various phases of ENSO at times produce similar snow, precipitation, and air temperature patterns across the region of interest, nevertheless, there is considerable variability from one event to the next. The best we can do at the present time is to couch predictions as probabilities of occurrence.

4. It has been demonstrated that air temperatures are highly correlated with snowfall in the GOA. Ongoing work in a related study indicates that the ultimate difference in air temperatures at any given station along the Gulf is a function of the advective temperatures that accompanies precipitation. The given monthly mean air temperature at a station for example is a function of what we might call the 'advective' component and the local' component which is a function of local constraints (topography, proximity to ocean). Whether precipitation falls as snow or rain at coastal stations is a function of the advective temperatures, inland however, local temperatures dominate as the mountains limit advection to the middle troposphere. As a result, we need to come to grips with what controls air temperatures over the North Pacific; what controls southerly flow from southwesterly and most importantly as noted above, what factors dictate the nature of southwest flow across the Gulf.

APPENDIX: INDICES EXPLAINED

Alaska Index: 700 mb height anomalies over Northwest Territory. Positive (negative) values indicate a (lower) higher amplitude ridge over eastern Alaska and northwest Canada- generally resulting in more (less) frequent southerly flow across the northern GOA. See PMEL website for values: http://www.beringclimate.noaa.gov/data

Arctic Oscillation [AO]: sometimes referred to as the Annular Mode and linked to the North Atlantic Oscillation. The AO is manifest as the speed of which air in the arctic spins around the North Pole. When the air is moving slowly (fast) the index is negative (positive) and cold artic air is more capable (less capable) of moving into the mid-latitudes.

El Nino & Southern Oscillation [ENSO]: is a measure of the SST in the equatorial region of the Pacific Ocean. Warmer than normal SST's in the eastern Pacific are called El Niño's while cooler than normal SSTs are La Nina's. Each phase generates its own weather/climate anomalies in the mid-latitudes, namely the position of the jet stream. El Niño's (positive index) often produce more frequently south flow into Alaska while La Nina's (negative index) enhance west-to-northwest flow.

North Pacific [NP]: based on the work of Trenberth & Hurrel (1994) this area-weight sea-level pressure of the Aleutian Low between 30^{o}N-65^{o}N and 160^{o}E-140^{o}W. When the index is large [>10] high pressure (low pressure) dominates over the eastern North Pacific. For example high pressure over the region often leads to increased western flow across the GOA while lower pressure [deeper than normal Aleutian Low] often results in enhanced southerly flow.

North Pacific Gyre Oscillation [NPGO]: represents changes in the surface water height of the North Pacific. Closely tracks with SST anomalies and is also highly correlated with the 'Victoria Pattern" of the eastern Pacific.
Oceanic Nino Index-adjusted[ONI-adj]: SST anomalies in the various Nino regions of the equatorial eastern/central Pacific.

Pacific Decadal Oscillation [PDO]: is a measure of the sea surface temperature anomalies in the North Pacific north of 20^{o}N. When the index is positive (negative) SST's are cooler (warmer) than normal in the mid-Pacific but warmer (cooler) than normal in the GOA and along the coast of western North America. Often a positive PDO is associated with a deeper (higher) than normal Aleutian Low.

Pacific North American Pattern [PNA]: is measured as 500 mb height anomalies are four points over the Pacific Basin and North America. Positive (negative) index indicates a higher (lower) amplitude ridge over western Canada.

Sib-AK: Stands for Siberian and Alaska Index, 700 mb height anomalies over eastern Siberia and northwest Canada. Closely linked with the Alaska Index. See PMEL website for details.

West Pacific [WP]: north-south 500 mb height anomalies over the Western Pacific.

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