El Niño and North American Snow Cover

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ABSTRACT

An investigation of the impact of El Niño/Southern Oscillation (ENSO) on North American (NA) snow cover was carried out using NOAA satellite data for the post-1971 period, and historical station data for a much longer 1915 to 1992 period. El Niño and La Niña snow cover composites were formed from the major events occurring in each time period following Groisman *et al.* (1994). For the satellite data, the compositing was based on five prominent El Niño and three prominent La Niña events. For the longer period of station data, 10-year composites of prominent events were able to be formed to give a more robust estimate of the average influence of tropical Pacific SST anomalies on NA snow cover. Comparison of the two sets of results revealed important differences particularly with respect to La Niña. The satellite La Niña composite showed major reductions in winter snow cover over the southern U.S. while the station data revealed a relatively weak La Niña influence on snow cover, with a tendency for increased snow cover in all months. The El Niño composites showed some regional similarities, especially reduced spring snow cover over western portions of the continent. Analysis of the significance of composite anomalies revealed that El Niño was associated with locally significant reductions in snow cover over western regions of the U.S. and Canada from December to April. La Niña was found to be associated with significant increases in winter snow depth over southern B.C. and the Prairies from January to April. In terms of NA snow cover extent (SE), the 10-year station data composite results revealed that El Niño was associated with significant reductions of SE in December. It is hypothesized that the enhanced December sensitivity of snow cover to El Niño conditions is related to a coincidence of the El Niño air temperature anomaly with the snow cover-temperature sensitive zone which is in its most westward position during December.

Key words: Snow cover, El Niño, La Niña

INTRODUCTION

El Niño events exert important influences on temperature, precipitation and snow cover over North America, especially in western regions (Ropelewski and Halpert, 1986; Groisman and Easterling, 1994; Groisman *et al.*, 1994; Cayan, 1996). El Niño events are typically associated with extensive winter warming, increased rainfall and less snow all of which have significant implications for snow and water resource based industries. Previous studies of ENSO influences on North American snow cover have been limited spatially (e.g. Brown and Goodison, 1996) or temporally (Groisman *et al.*, 1994) by the nature of the available snow cover datasets. Groisman *et al.* (1994) used NOAA satellite-derived snow cover data for the 1972-1992 period to map the difference in the fraction of time with snow cover between ensemble averages of El Niño and La Niña events. The results suggested that in the first half of the hydrological year, El Niño events were accompanied by an expanded snow cover extent (SE) over the United States, while at the same time, the SE was below normal in southern Canada. In the second half of the hydrological year, Groisman *et al.* (1994) observed that El Niño events were accompanied by an abnormal retreat of SE over

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the entire NH. Brown and Goodison (1996) explored the ENSO-snow cover relationship in several regions across southern Canada over a much longer 1915 to 1992 period. The only significant correlations between snow cover and Pacific SST anomalies were observed over western Canada, and it was concluded that the ENSO-snow cover relationship over southern Canada was highly variable both in time and space.

The Groisman *et al.* (1994) study was a useful first attempt to look at large scale influences of ENSO on snow cover. However, it was severely constrained by the short length of available satellite data, and it is possible that results from their recent 20 year period may not represent a "typical" response in light of the major reorganization of atmospheric circulation over the North Pacific and North America that occurred in the late 1970s (Trenberth, 1990; Leathers and Palecki, 1992). In addition, Groisman *et al.* (1994) presented their results in terms of El Niño minus La Niña which make it difficult to determine which phase of ENSO is responsible for the observed difference patterns. The aim of this study therefore, was to expand and extend the Groisman *et al.* (1994) analysis by applying a new historical gridded snow cover dataset for the United States and southern Canada which covered a considerably longer 1915-1992 period. The main objectives of the extended analysis were to: (1) carry out separate investigations of El Niño and La Niña composite snow cover anomaly patterns to obtain a clearer picture of the relative importance of each phase of ENSO e.g. Cayan (1996) observed that La Niña had the stronger impact on snow water equivalent anomalies in the U.S. Rocky Mountains; (2) compare the satellite and historical data results to determine the representativeness of conclusions based on satellite-era data; and (3) estimate the statistical significance of anomalies in North American SE during ENSO years to determine if the ENSO-SE signal is stronger than the natural variability in SE.

DATA SETS

Satellite Data

The NOAA satellite snow cover data set used in this study are described in Robinson *et al.* (1993). The data consisted of digitized weekly charts of snow cover derived from manual interpretation of visible satellite imagery by trained meteorologists. The charts are digitized on an 89 x 89 polar stereographic grid for the Northern Hemisphere (NH), with cell resolution ranging from 16 000 km2 to 42 000 km^2 (Robinson *et al.*, 1993). The data are binary in format with cells interpreted to be at least 50% snow covered represented by a "1". While regular satellite monitoring of NH snow cover began in November 1966 (Dewey and Heim, 1982), the sub-point resolution of the pre-1972 satellites was ~4.0 km compared to 1.0 km with the VHRR launched in 1972 (Robinson *et al.*, 1993). A project to re-chart and digitize the pre-1972 data is being completed at Rutgers University which will extend the NOAA record back to 1966 (D. Robinson, *pers. comm.*). Until these data are available, only data from 1972 on are considered sufficiently accurate for climate studies. The data were obtained from D. Robinson (*pers. comm.*) and contain the corrections recommended by Robinson *et al.* (1991). In addition, the Rutgers weighting scheme (Robinson, 1993) was used to correctly partition weekly charts into appropriate months for computing seasonal snow cover duration. Linear interpolation was used to account for a missing chart in week 51 of 1972. Robinson (1991) found that station- and NOAA-derived estimates of snow cover agree closely on a seasonal time scale given a good network of stations in non-forested, non-mountainous terrain.

Station Data

In Canada, daily snow depth observations are only available in digital format from 1955 onward in the official Atmospheric Environment Service (AES) daily climate archive. A data rescue project was undertaken in 1995 and 1996 as part of the CRYSYS Project (Goodison and Brown, 1997) to digitize a considerable volume of daily and weekly snow observations that were not in the daily climate archive. These additional data plus the existing digital snow depth data were subject to rigorous quality control checks following Robinson (1989), with missing values filled using a simple snow accumulation and melt model driven with daily climate data (Brown and Braaten, 1998). The resulting daily snow depth dataset is characterized by predominantly reconstructed values prior to ~1940, and predominantly observed values after ~1950. To check whether this caused any discontinuity in computed snow cover information, regional snow cover duration series from this dataset were compared with those presented by Brown and Goodison (1996) that were completely reconstructed from daily climate data. The comparison revealed no evidence of any inhomogeneity in snow cover. To reduce the impact of increasing station density over time (the number of stations increased four-fold in 1980), stations were excluded which did not have at least 60 years of complete (less than 20% missing data during November-April) daily snow depth data in the 1915 to 1992 period. The 154 stations that satisfied these criteria were mainly located in southern Canada south of ~55°N.

Daily snow depth data for the United States were taken from the 195 station dataset of Easterling *et al.* (1997). These data are a subset of the National Weather Service principal climatological station network and cover the period 1893-1992. In general, stations have snow depth data for the seven month period October to April. The stations included in this dataset were selected to form a relatively stable station network over time so there was no need to apply restrictions on the length of data at each observing site. These data were subject to quality control procedures by the National Climatic Data Center.

Station Data Gridding

To facilitate the analysis of the station data, daily snow depths in the two station data sets were interpolated to the same grid as the NOAA satellite data for the 1915 to 1992 period using an inverse distance weighting scheme and a maximum search radius of 200 km. 1915 was selected as the earliest date following Brown and Goodison (1996) who found that the Canadian station network was spatially stable from ~1915. The interpolation of daily snow depth information allowed the compilation of monthly snow depth statistics (minimum, maximum, mean, median, standard deviation) in addition to monthly snow cover duration. Monthly snow cover duration was calculated for a range of depth thresholds (0, 2, 7 and 14 cm) and expressed as a % (number of days with snow cover/ total number of days in month). Comparison of SE derived from the station data with the satellite data revealed that the highest agreement was obtained for the 2 cm threshold depth confirming previous findings by Robinson (1991). A total of 349 stations were used in the interpolation: 154 from southern Canada and 195 over the contiguous United States. Only gridpoints with complete data in the 1915 to 1992 period were used to investigate ENSO influences on North American snow covered area. The spatial distribution of gridpoints with complete data in the 1915-1992 period is shown in Figure 1 for January.

METHODOLOGY

The methodology used for examining El Niño and La Niña influences on NA snow cover followed Groisman *et al.* (1994). This involved computing the average snow cover at each gridpoint for composites formed from the strongest El Niño and La Niña events occurring during the period of interest. For the satellite data, the same composites were used as Groisman *et al.* (1994) since the 1993-1996 period of additional satellite data did not

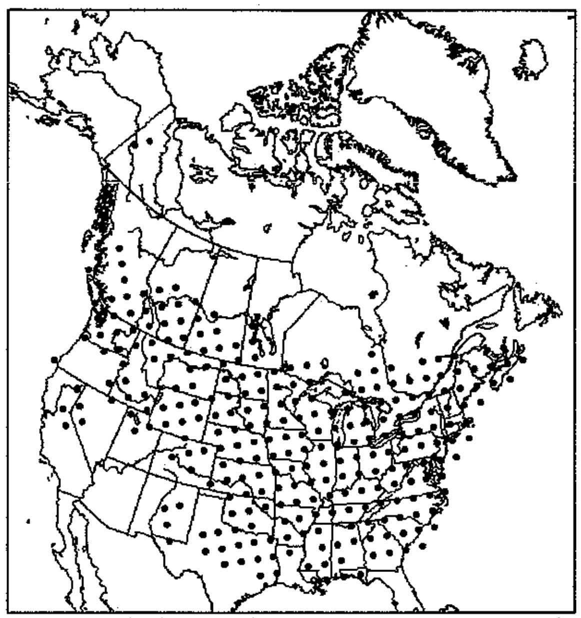

Figure 1: Distribution of gridpoints with complete data in the 1915-1992 period with a non-zero land cover fraction. A land/sea was applied when computing snow-covered area.

include any new significant El Niño or La Niña events. Groisman *et al.* (1994) used the average value of the Southern Oscillation Index (SOI) over the fall and winter period to select 5 prominent El Niño events (1972/73, 1977/78, 1982/83, 1986/87 and 1991/92) and 3 prominent La Niña events (1973/74, 1975/76 and 1988/89). The longer 1915/16 to 1991/92 period of data in the station grid allowed 10-year El Niño and La Niña composites to be formed by selecting the 10 top and bottom ranked values of the SOI averaged over the November-April snow cover season. With the exception of the 1957/58 El Niño year, all the years selected had average standardized values of the SOI that equaled or exceeded ±1.0. The 10 years identified are summarized in Table 1 with the years selected by Groisman *et al.* (1994) indicated with an asterisk. It is apparent that the El Niño and La Niña events which occurred during the period of satellite data coverage include some of the strongest events observed this century (6 of the 8 events selected by Groisman *et al.* have top 5 rankings). Snow cover anomaly maps were then computed as the difference in snow cover between the El Niño and La Niña composite average, and the average snow cover over the period of available data (excluding the extreme El Niño and La Niña events).

The composite analysis was also carried out for monthly values of North American SE. For the station data, a monthly snow cover area index was derived by summing monthly snow cover over gridpoints with complete data in the 1915-1992 period. The snow cover index was highly correlated with NOAA-derived SE for the 6 month period from November to April. Both snow cover series were expressed as standardized anomalies with respect to a common 1972-1992 reference period.

Table 1: The 10 strongest El Niño and La Niña events in the 1915/16 to 1991/92 period based on the average November-April value of the standardized SOI. The events selected by Groisman *et al.* (1994) are indicated with an asterisk.

El Niño	La Niña
1982/83* -3.25	1973/74* 2.10
1991/92* -2.05	1970/71 1.63
1925/26 -1.93	1917/18 1.57
1986/87* -1.67	1988/89* 1.37
1940/41 -1.57	1975/76* 1.35
1977/78* -1.38	1916/17 1.33
1918/19 -1.15	1955/56 1.13
1965/66 -1.10	1928/29 1.08
1941/42 -1.00	1938/39 1.05
1957/58 -0.87	1924/25 1.05

The presence of long-term trends in snow cover could contaminate a composite analysis if the years forming the composites were preferentially grouped. Brown (1998) observed a significant (0.05 level) increase in NA SE in the months of November, December and January over the 1915 to 1997 period. However, this trend is unlikely to exert a major influence on the results of this study as both sets of composite years are relatively evenly spread over the 78 year period. Secular changes in snow cover were therefore ignored in computing gridpoint composite averages for contouring and display. In the composite analysis of NA SE, however, secular variation in continental snow cover extent was taken into account by expressing anomalies as deviations from a 9-year running mean. To obtain an indication of the local significance of snow cover anomalies in El Niño and La Niña composites, the Student t-statistic was computed for the difference in the composite mean and the 1915-1992 average at each gridpoint. This did not take into account spatial autocorrelation but nevertheless provided a useful internally consistent indicator of the relative importance of snow cover changes in each month.

RESULTS

Comparison of monthly satellite and station-based composites for changes in snow cover

A comparison of the satellite and station-based El Niño and La Niña composites is provided in Figures 2 and 3 for the months of December, February and April [**Note: due to difficulties providing adequate black and white versions of the colour images, Figures 2-5 are provided on a website for viewing at** *http://www1.tor.ec.gc CRYSYS/brown98/*]. These three months were selected for logistical reasons to reduce the number of plot images to a manageable level. Animations of the full monthly series are provided on the above website. The satellite El Niño composite results initially show a major expansion of snow cover over the continent in November which is quickly replaced with a reduction in snow cover over the eastern United States in December. This negative anomaly then migrates westward over the Great Plains in February, and intensifies to cover most of the western United States and Canada in April. Slight increases in snow cover are indicated along the western and southern boundaries of the continental snowline during winter. These results agree well with Groisman *et al.* (1994, p. 1648) who reported that "El Niño events are accompanied by an unusual expansion of the SE over the contiguous United States, while at the same time the SE is below normal in southern Canada". The station data results exhibited some similarities to the satellite composites in February and April. However, they differed in two important respects. First, there was no November expansion of snow cover observed in the station data results, and second, the station results suggest a more widespread and persistent reduction in winter snow cover over the western half of the continent during El Niño events. This difference is most noticeable in December, and begs the question as to whether the station data are representative of snow cover variations over the more mountainous western region of NA. To address this question, the satellite era composite analysis was performed with the station data for the months of November and December (it was not possible to carry this out in the second half of the snow year as the station data did not include all the snow cover months in the 1992/93 El Niño event). A comparison of the satellite and station El Niño results for December are provided in Figure 4. With the exception of California and Nevada, the two sets of results are quite similar, and the November station results (not shown) revealed the same widespread expansion of snow cover observed in the satellite composite. This finding suggests that the differences observed between the two sets of composite results in Fig. 2 are related to the years included in the composites rather than to low-elevation bias in the station data.

The La Niña composite comparison in Fig. 3 revealed a major lack of agreement between the station and satellite results. The station results suggest that on average, La Niña had less of an impact on snow cover than El Niño, with an overall tendency for slightly increased snow cover throughout the snow season. In contrast, the satellite results suggested that La Niña was associated with major reductions of snow cover over the eastern United States and major increases in snow cover over the Rocky Mountains. These patterns were stronger than those observed in the corresponding satellite El Niño composites. This different result is likely related to the small number of La Niña events which have occurred during the post-1971 period (three), and to the relatively short period of time (15 years) spanning the three events. During such a short period, the atmospheric circulation may well be in a different state from the long-term average. For example, the atmospheric circulation over NA is known to have experienced significant re-organizations in the 1960s (Knox *et al.*, 1988; Shabbar *et al.*, 1990) and again in the late 1970s (Trenberth, 1990; Leathers and Palecki, 1992). The latter shift in the PNA pattern coincided with a marked reduction in winter snow depths over large areas of Canada (Brown and Braaten, 1998). Further evidence for a recent change in the relationship between atmospheric circulation and snow cover was provided by Frei *et al.* (1998) who determined that the interannual variability in NA snow cover had increased noticeably during the last three decades. Thus while the station data results may provide a better estimate of the <u>average</u> response of snow cover to El Niño and La Niña events, the impact of any single El Niño and La Niña event on snow cover will depend on the prevailing atmospheric circulation anomaly patterns during that winter, in particular, the strength and sign of the PNA pattern which has been shown in several studies to be closely linked to temperature, precipitation and snow cover variability over the continental interior and western regions of North America (Gutzler and Rosen 1992; Brown, 1995; Brown and Goodison, 1996, Moore and McKendry, 1996).

Student t-test results for locally significant changes in snow cover and snow depth

The Student t-statistic was applied to determine whether the 10-year El Niño and La Niña station data composite means were significantly different from the mean snow cover conditions observed over the entire 1915-1992 period. This analysis was applied to monthly snow cover as well as to monthly snow depth as the latter is not affected by the "signal saturation" problem in regions where winter snow cover is 100% in all years. The assignment of statistical significance to a spatial domain (or "field significance") is complicated by the spatial autocorrelation of data (Livezey and Chen, 1983). There was not time to complete a full Monte Carlo analysis for field significance in this preliminary paper. However, to determine whether regional patterns of locally significant snow cover anomalies could be generated by chance, a composite analysis was carried out for a limited number of composites formed from random selections of 10 years where the absolute average value of the SOI index over the snow season was less than 0.3. The composites were therefore comprised of years without any direct El Niño or La Niña influences. The results revealed that spatially coherent areas of locally-significant snow cover change could indeed be generated by "chance". However, these patterns were only observed in individual months.

Visual analysis of monthly plots of the El Niño and La Niña t-statistic values for snow cover and snow depth revealed two patterns of locally significant snow cover anomalies which were consistent over several months (Fig. 5). First, El Niño was associated with locally-significant reductions in snow cover over western portions of the continent which persisted from December to April. Second, La Niña was associated with locally significant increases in snow depth over southern B.C. and the Prairies from January to April. These results confirm the conclusion of Brown and Goodison (1996) that ENSO influences on snow cover are mainly confined to the western half of the continent. The band of increased snow depths in the La Niña results in Figure 5 corresponded closely to the area of significantly increased winter precipitation observed across southern Canada during La Niña years by Shabbar *et al.* (1997).

Analysis of El Niño and La Niña influences on NA monthly snow cover extent

North American SE is a more robust variable to test for El Niño and La Niña influences as this represents an integrated response over the entire continent. Two data series were used in this analysis: (1) SE computed from the NOAA satellite data set and (2) a NA SE index derived from the gridded station data by summing snow covered area over all gridpoints with complete data in the 1915-1992 period. Both SE time series were converted to standardized anomalies with respect to a common 1972-1992 reference period. Brown (1998) showed that the two anomaly series were highly correlated for the months of the November to April, so the two series were combined (SE index from 1915-1971 and satellite SE from 1972), and expressed as deviations from a running 9-year mean to remove any influence of secular changes in SE on the composite averages. The t-test was then applied to determine the significance of differences in NA SE during El Niño and La Niña composite years for (a) the 10-year composites selected from the 1915-1992 period, and (b) the composites selected from the satellite data period by Groisman *et al.* (1994).

The two sets of results (Fig. 6) gave quite different results which was expected based on the different anomaly patterns observed in Figures 2 and 3. The 10-year composites results (Fig. 6a) indicated that the maximum effect of El Niño occurred in December, when SE was significantly (0.05 confidence level) below average. El Niño also had a noticeable effect in reducing April SE but this was not statistically significant. La Niña was associated with increased SE across all six months but this was not statistically significant. In contrast, the satellite-period composites indicated that January SE was significantly (0.05 level) below average for the La Niña composite, and that El Niño was only associated with a reduction in snow cover during April (not statistically significant). These results clearly indicate that La Niña was the main driving force in generating the NA snow cover reduction changes presented in Groisman *et al.* (1994).

The December peak of reduced SE in El Niño years is an interesting finding, but it is one that makes physical sense based on the temperature sensitivity analysis of North American snow cover and snowfall carried out by Karl *et al.* (1993). Karl *et al.* identified large seasonally-varying temperature-sensitive regions of NA where snow cover, air temperature and snowfall were all highly correlated. In these regions, they reasoned that maximum air temperatures were close to freezing which meant that relatively small changes in temperature changed the partitioning of precipitation into rain or snow which had an important impact on snow cover. While the precipitation signal associated with El Niño exhibits considerable regional variability, the air temperature signal exhibits a well-defined warming anomaly of 2 to 4°C penetrating NA from the NW which develops in December and is most pronounced in January.

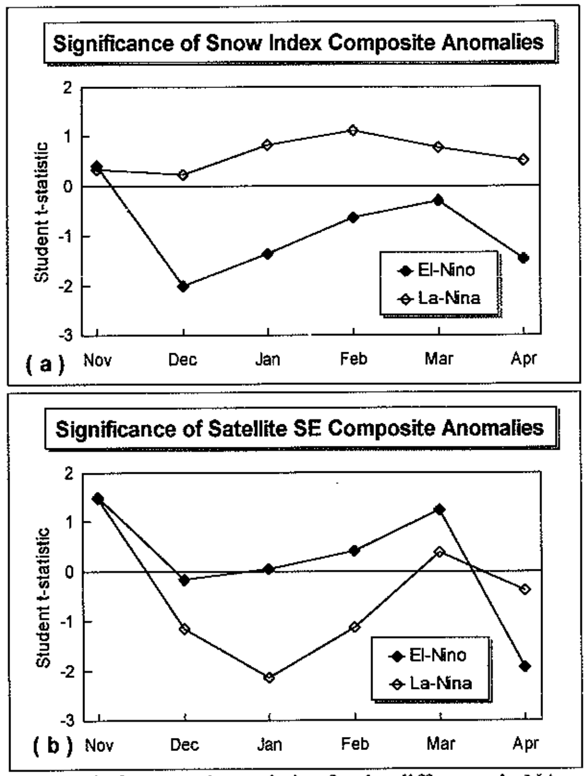

Figure 6: Computed t-statistics for the difference in NA SE in El Niño and La Niña composite years for (a) station-derived snow cover index from 1915-1992 using 10-year composites, and (b) NOAA satellite data from 1972 using the El Niño and La Niña composites of Groisman *et al.* (1994).

A comparison of the monthly snow cover temperature sensitive regions identified by Karl *et al.* (1993, Fig. 4c) with monthly El Niño temperature anomaly patterns revealed that the two patterns coincide to a large extent in December when the snow cover-temperature sensitive region is in its most westward position over the mid-latitudes of North America. In January, the two patterns are displaced with the snow cover-temperature sensitive region located over the south-central U.S. and the maximum El Niño temperature anomaly located over the northern Great Plains and Canadian Prairies. The ehnanced El Niño sensitivity in December is also consistent with the findings of Leathers and Robinson (1993) of an enhanced positive snow cover-temperature feedback mechanism in December where snow cover anomalies contribute to large-scale modification of atmospheric temperature and pressure anomalies over the contiguous United States.

CONCLUSIONS

The extension of the preliminary ENSO snow cover analysis presented in Groisman *et al.* (1994) revealed that El Niño and La Niña composite snow cover anomalies formed from the recent period of satellite data were quite different from the anomalies obtained with a larger sample of El Niño and La Niña events. During the satellite era, La Niña events had the largest impact on reducing winter snow cover, contrary to results obtained with larger sample sizes where El Niño was found to be associated with significant winter snow cover reductions, and La Niña with increases in snow cover. This difference underscores the variability in ENSO snow cover response which is only one of a number of factors influencing mid-latitudinal climate and snow cover, and highlights the importance of secular changes in atmospheric circulation which have been shown to be associated with widespread changes in snow cover over Canada (Brown and Braaten, 1998).

Analysis of the local significance of regional patterns of snow cover change in El Niño and La Niña years revealed that the most persistent anomalies were located over the western portions of the southern Canada and the northern U.S. during winter. El Niño was associated with locally-significant reductions in snow cover over the northern Great Plains and Prairie region which persisted from December to April, while La Niña was associated with locally significant increases in snow depth over southern B.C. and the Prairies from January to April.

Analysis of the significance of El Niño and La Niña events on North American snow cover extent revealed that, on average, El Niño was only associated with a significant reduction of snow cover extent in the month of December. It was argued that this particular result was related to the El Niño temperature anomaly coinciding with the zone of maximum snow cover-air temperature sensitivity, which is in its most westward location over the mid-latitudes of North America during December (Karl et al. (1993), and to enhanced December snow cover-temperature feedbacks following Leathers and Robinson (1993). The results of this analysis will be useful for seasonal forecasting and for validating snow cover simulations from transient runs of global climate models.

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