Winter-Spring 2001 United States Streamflow Probabilities based on Anticipated Neutral ENSO Conditions and Recent NPO Status

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Outlook. An analysis of historical floods and seasonal streamflows during years with neutral El Niño-Southern Oscillation (ENSO) conditions in the tropical Pacific and "negative" states of the North Pacific Oscillation (NPO) in the North Pacific—like those expected next year—indicates that (1) chances of having maximum-daily flows next year that are near the long-term averages in many rivers are enhanced, especially in the western states, (2) chances of having near-average seasonal-average flows also may be enhanced across the country, and (3) locally, chances of large floods and winter-season flows may be enhanced in the extreme Northwest, chances of large winter flows may be diminished in rivers in and around Wisconsin, and chances of large spring flows may be diminished in the interior southwest and southeastern coastal plain. The background, methods, and forecast results that lead to these statements are detailed below, followed by a summary of the successes and failures of last year's streamflow forecast by Dettinger et al. (1999).

Background. Recent forecasts of ENSO status in the upcoming year by both statistical and dynamical methods are calling for mild warming to a near-normal state of the tropical Pacific by next winter (examples are available in the June 2000 Experimental Long-Lead Forecast Bulletin and from the National Centers for Environmental Prediction and International Research Institute for Climate Prediction, at http://iri.ldeo.columbia.edu/climate/forecasts/sst/). Such near-normal conditions yield little anomalous forcing of the extratropical weather systems that bring precipitation, temperatures, and ultimately streamflow to the United States, and historically have resulted in only small changes in the probabilities of various streamflow extremes. Recently, though, the long-term state of the North Pacific climate, as indexed by the NPO (originally described by Walker and Bliss, 1932; also commonly called the Pacific Decadal Oscillation, PDO, e.g., by Mantua et al., 1997) has varied in ways that may also be influencing streamflow probabilities (Gershunov et al., 1999; McCabe and Dettinger, 1999; http://topex-www.jpl.nasa.gov/discover/PDO.html). Together the

forecasted neutral state of ENSO and recent variations of the North Pacific climate provide a basis for estimating probabilities of streamflows next year that are significantly different from random chance in many rivers of the conterminous United States. In this report, therefore, the probabilities that United States streamflows from December 2000 through July 2001 will be in upper, middle, and lower thirds (terciles) of historical flows are reported based on previous years in which near-neutral ENSO conditions followed warm ocean temperatures in the central North Pacific like those observed in the last few years. The relatively slow, orderly evolution of El Niño-Southern Oscillation and Pacific Decadal Oscillation episodes (Dettinger et al., 2000), the accentuated dependence of streamflow upon ENSO (Cayan et al., 1999), and the expected long lags between precipitation and flow encourage us to provide the following guidance as to the most likely ranges for next year's river flows.

Approach. Historical daily flow records from 1,253 streamgaging stations cross the US were used to compute flood statistics and "winter" (December-March) and "spring" (April-July) seasonal averages for each streamgaging station's period of record. Seasons were defined in these terms in order to differentiate between winter-season rainfall/early-snowmelt runoff and the delayed springtime snowmelt runoff. The streamflow records analyzed are from streamgaging stations in the U.S. Geological Survey's Hydroclimatic Data Network (Slack and Landwehr, 1992), a network of streamgaging stations determined to be largely free from human influences or station changes. Observations between 1988 and (as recently as) 1998 have been compiled and included for the streams analyzed here. The streamgaging stations analyzed here provide streamflow series that begin no later than 1948 and end no earlier than 1991.

In order to estimate streamflow probabilities conditioned by the forecasted near-neutral ENSO conditions, historical streamflow records were analyzed to determine the limits of period-of-record upper, middle, and lower terciles of flood and seasonal flow

rates. Then the fraction of years with near-neutral ENSO conditions that fell in each streamflow tercile were compared to the 33% that would be expected if, instead, the years had been chosen at random. Sites at which streamflow records for at least 10 near-neutral ENSO years and for which the near-neutral-ENSO fractions deviated significantly from the 33% expected (at 95% confidence levels; Le, 1998) were judged to reflect locally significant deviations of the probabilities of streamflow conditions for next year. Then the number of such deviations was compared to the numbers found in similar analyses of the streamflow records when the chronology of historical ENSO conditions used in the calculations was randomized 1,000 times; this Monte Carlo comparison provided estimates of the field significance of the observed probabilities (Livezey and Chen, 1983). When streamflow statistics in years with near-neutral ENSO conditions were compared to overall historical streamflow probabilities, the field significance for the "near-neutral ENSO" statistics was low; to obtain greater field significance, information about the recent state of the NPO also had to be included in the analyses.

The effect of the NPO on ENSO teleconnections in the United States has been noted by Gershunov et al. (1999), McCabe and Dettinger (1999), and Cole and Cook (1998), and motivates us to condition the probability estimates for next year's streamflows by recent NPO status. This conditioning, however, requires a choice as to how to index or forecast next year's NPO state. The NPO (or PDO) is indexed in terms of the first principal component of North Pacific sea-surface temperatures (SSTs), e.g., as in Mantua et al. (1997), which has interannual as well as interdecadal components. Most attention has focused on the decadal and interdecadal aspects of this index and, often, it has been discussed in terms of regimes of North Pacific climate (e.g., Mantua et al., 1997; Gershunov et al., 1999). This focus on regimes has resulted in more attention paid to the question "When will the next regime shift occur (or has a regime shift already occurred)?" rather than to "What will be the state of the NPO (and thus North Pacific SSTs) next year?." The former question is at the heart of understanding the decadal aspects of climate in the Pacific/North American sector. The latter question, however, is more pressing here, because the atmosphere and thus North American weather responds quickly to the current state of the SSTs. Thus the state of SSTs in the North Pacific next year are more important for anticipating next year's streamflow than is knowledge of which long-term-average "regime" applies. Decadal NPO regimes are interrupted by short-term reversals often enough so that, even with the advantage of perfect hindsight, a given

year's NPO sign reflects the concurrent interdecadal regime yields a correct forecast of the annual average of NPO only 77% of the time since 1930. Without hindsight to guide us and (for now) lacking a better predictor of NPO status, we note that using NPO's strong interannual persistence to anticipate that next year's NPO sign will be like that of the average of the previous 1, 2, or 3 years' average NPO yields a correct estimate 74% of the time (for each of these averaging intervals), during the same period. Thus, little "forecast" skill is lost by simply assuming that next year's NPO sign will reflect the average of the NPO index over the last two years; this average is used here and suggests that the NPO sign next year is most likely to be negative (with anomalously warm SSTs in the western and central North Pacific and anomalously cool SSTs along the coast of North America).

Probabilities that seasonal flows will be in the upper, middle, or lower tercile of their historical distributions during years with near-neutral ENSO (NN) conditions in the tropical Pacific and with two preceding years during which the NPO index was, on average, negative were determined as follows: At 816 sites with records that include 10 or more years of record with neutral ENSO and negative NPO (NN/negative NPO) conditions, the historical NN/negative NPO flows were compared to the terciles of flow from the entire period of record. Streamgaging stations at which NN/negative NPO flows historically have occurred in upper, middle, and lower terciles beyond the 33% of occurrences that would be expected of a random distribution of flows, with 95% confidence, are plotted in the panels of Figs. 1-3 as circles with radii proportional to the deviation of the NN/negative NPO flow probabilities from 33%. Black dots correspond to anomalously frequent occurrences and white dots correspond to anomalously rare occurrences. Because the probability patterns are much weaker than those generated for the La Niña/ negative NPO conditions during last winter and spring's flows (Dettinger et al., 1999), a field-significance test (described above) was applied, and only those maps (with one exception) that yielded field-significance levels of about 90% or greater are shown here. Details and a complete listing of river-by-river probabilities can be found online at http://meteora.ucsd.edu/cap/ nnnpo.html.

Forecast. The largest, most field-significant probability anomalies associated with NN/negative NPO streamflows are for "annual-flood" series, which consist of the time series of the single largest daily flows from each year of record at each streamgaging station. Anomalous probabilities of annual floods in upper, middle, and lower terciles of the historical record are shown in Fig. 1. Notably, probabilities of middle-tercile

a) Anomalous Probabilities of Maximum Daily Flows in UPPER TERCILE during OCTOBER-SEPTEMBER of a No-Nino/Negative-NPO Year
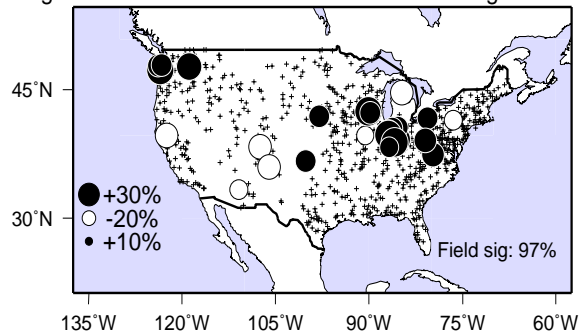
b) Anomalous Probabilities for MIDDLE-TERCILE Maximum Daily Flows
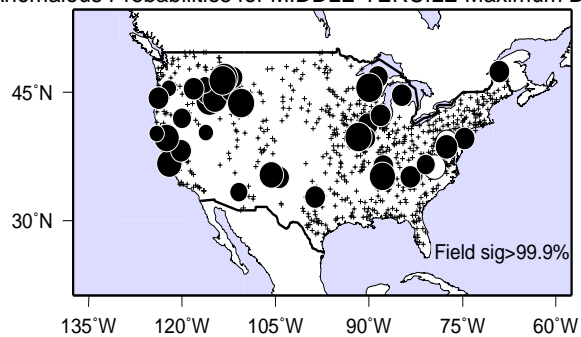
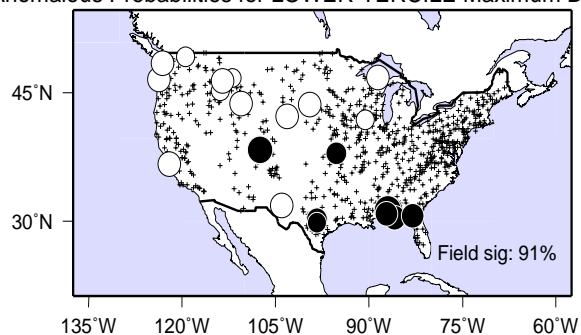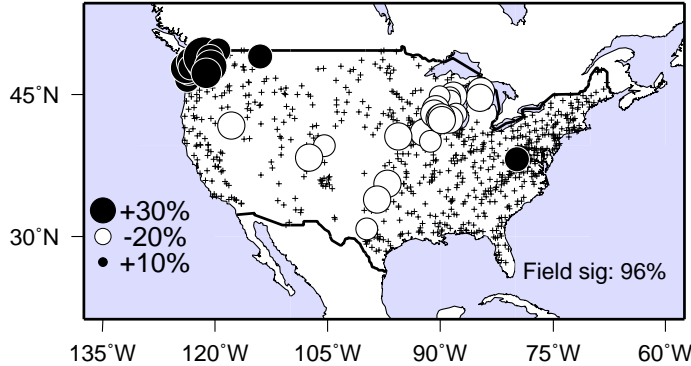## c) Anomalous Probabilities for LOWER-TERCILE Maximum Daily Flows

Figure 1. -- Anomalous probabilities of occurrence of a maximum-daily flow (annual flood) during October 2000 to September 2001 that is among the (a) upper tercile, (b) middle tercile, and (c) lower tercile of historical maximum-daily flows at rivers in the conterminous United States, based on historical flows during years with neutral ENSO and negative NPO states. Black dots indicate rivers with anomalously high probabilities of occurrence (beyond two-tailed 95% confidence intervals); white dots indicate rivers with anomalously low probabilities (beyond 95% confidence intervals); dots are scaled so that the radii are proportional to the probability in excess of 33% and small crosses indicate rivers that do not deviate from 33% by more than the 95% confidence bounds.

floods are enhanced at a number of sites across the nation (Fig. 1b, with a very high field-significance level), with a particular clustering of enhanced probabilities in western rivers. Probabilities of upper-tercile floods are enhanced in some rivers in Indiana, Illinois, and the Ohio River drainage, as wells as in scattered rivers in the extreme northwest (Fig. 1a). Probabilities of lower-tercile floods are reduced in the northwest and enhanced in the Florida Panhandle region (Fig. 1c, but with a modest field-significance level).

Anomalous probabilities of seasonal flows historically have been less conditioned by NN/negative NPO years. The anomalous probabilities for winter-average flow rates (spanning December to March) are illustrated in Figure 2, for upper-tercile flows (2a, with a high field-significance level) and for middle-tercile flows (2b, with a small field-significance level but shown here to illustrate the tendency for enhancement of middle-tercile probabilities in all seasons). Probabilities of upper-tercile winter flows are enhanced in many rivers of the extreme northwest and are reduced in rivers in Wisconsin and the upper central Mississippi Valley. As with the annual-flood series, there is a broad, almost nationwide tendency for enhancement of middle-tercile flow probabilities in winter. Historically, spring-average flow rates have been even less conditioned by NN/negative NPO years than have winter rates, and neither of the probability maps shown for spring-average flows in Fig. 3 reaches a 95% field-significance level. Locally, though, the concentration of reduced probabilities of upper-tercile springtime flows in southeastern coastal rivers and interior southwest (Fig. 3a) imply less chance of extremely high spring flows there. As with the annual-flood series and winter flows, enhanced probabilities of middle-tercile spring flows are relatively common across the Nation (Fig. 3b), with a particular concentration in north coastal California and in rivers around Des Moines. The historical influences of NN/negative NPO conditions on the probabilities of lower-terciles seasonal flows in winter and spring were not strong enough to provide any statistical confidence in predictions of low flows; this does not mean that such flows are unlikely, only that they are not unusually unlikely.

a) Anomalous Probabilities of Seasonal Flows in UPPER TERCILE
during DECEMBER-MARCH of a No-Nino/Negative-NPO Year

b) Anomalous Probabilities of Seasonal Flows in MIDDLE TERCILE
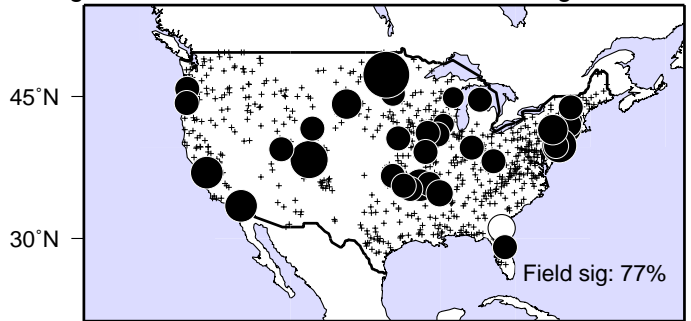during DECEMBER-MARCH of a No-Nino/Negative-NPO Year

Figure 2. -- Same as Figure 1a and 1b, except for seasonal-mean flows during December-March.

Overall, streamflow probabilities associated with the forecasted NN/negative NPO conditions next year are much less anomalous than those that were associated with strong La Niña conditions this year (Dettinger et al., 1999). Consequently, as noted previously, the primary insight from the historical record concerning next year's flows is that (1) chances of middle-tercile floods in many rivers are enhanced, especially in the western states, (2) chances of middle-tercile seasonal-average flows may also be enhanced across the country, and (3) locally, chances of upper- and lower-tercile flows in rivers of the extreme northwest, southeast, and elsewhere (as indicated in text and figures) may be enhanced. The enhanced chances of middle-tercile flows are compensated by probabilities reductions that are shared by both upper and lower terciles, and thus the changes reflect a narrower-than-climatological probability distribution rather than a shift of the distributions in one direction or the other. The tests applied here provide reasonable confidence levels but, for the most part, the actual probabilities changes are neither large in magnitude nor large in spatial extent.

Retrospective View of Winter-Spring 2000 Streamflow Patterns: Weather and streamflow patterns

(Figs. 4a and 4b) during the winter and spring of 2000 deviated markedly from the canonical La Niña pattern that was projected by Dettinger et al. (1999). On the west coast, precipitation was centered too far south to form the expected "northwest wet/southwest dry" pattern that is usually associated with La Niñas (Dettinger et al., 1998); farther east, the north-central states were wetter than would have been expected and the Appalachian Mountains drier. Perhaps as importantly, though, temperatures were generally warmer than usually would be expected of a La Niña year, and this had important implications for snowpack development and runoff timing in many areas. Overall, the winter-streamflow patterns anticipated by Dettinger et al. (1999) underpredicted flows at more sites than it correctly predicted the tercile for seasonal flow and overpredicted at about as many sites as it correctly predicted. Specifically, during winter 2000, higher flows (upper- and middle-terciles) occurred at 83 streams where lower-tercile flows were projected; upper- and lower-tercile flow forecasts were accurate at 53 streamgaging stations; and lower flows occurred at 46 sites where upper-tercile flows were expected (Fig. 4c). These verification statistics are based on a subset of 592

a) Anomalous Probabilities of Seasonal Flows in UPPER TERCILE during APRIL-JULY of a No-Nino/Negative-NPO Year
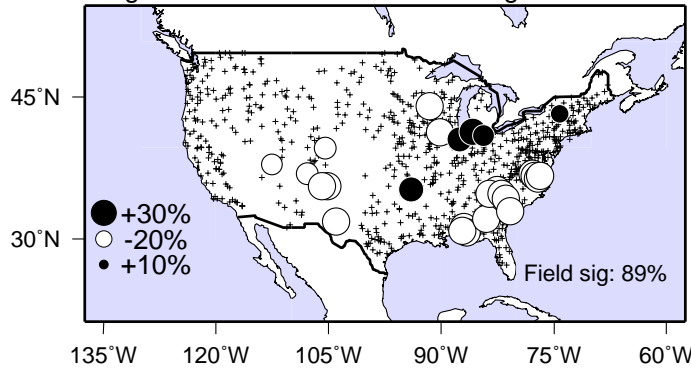
b) Anomalous Probabilities of Seasonal Flows in MIDDLE TERCILE during APRIL-JULY of a No-Nino/Negative-NPO Year
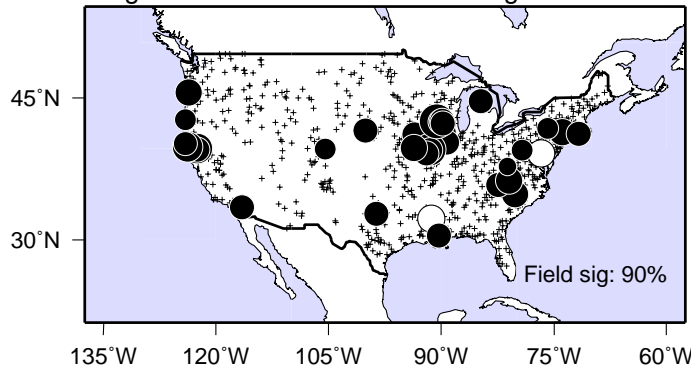

Figure 3. -- Same as Figure 1a and 1b, except for seasonal-mean flows during April-July.

forecasted sites for which winter-flow observations could be obtained at the time of this writing, and reflects observations from the February 17-March 31 period when they were available. Also, since middle-tercile flows were not explicitly considered in Dettinger et al. (1999), sites where middle-tercile flows would have been expected to be most likely are not included in this verification. Between restrictions of the verfication by the limited availability of streamflow data a few months old, and by limitation to sites with strong probability anomalies and to sites where either upper- or lower-tercile flows were most likely, the number of verification sites was reduced to 182 in winter and 213 in spring. Due to the southward shift of precipitation (relative to other La Niña years) and, in part, to warm conditions that resulted in earlier runoffs, many of the rivers in the northwest were underpredicted. Wetter than expected conditions also prevailed in Wisconsin and neighboring areas and in northern New England (Fig 4c).

By spring 2000, flows along the northwest coast were less than expected (due to small winter snowpacks), but in the interior west, streamflows reflected some of the expected "northwest wet/ southwest dry" La Niña pattern (Fig. 4b). Also, the low

flows anticipated for the upper Mississippi basin, southwest, and southeast had developed as expected (http://enso.unl.edu/monitor/monitor.html). Consequently, for the sites with flow data available to us from April 1 - June 13, 2000, the number of correctly anticipated terciles was better in the spring, with 95 correctly anticipated terciles compared to 45 underpredictions and 74 overpredictions. Primary areas where the spring-flow projections in Dettinger et al. (1999) erred are in the extreme Northwest and Southeast where flows have been higher than expected, and in eastern Texas, other Northwestern rivers, in the Carolinas and New England, and in Illinois and Indiana where flows were overpredicted, and in Appalachian rivers where the expected La Niña wetness never occurred (Fig. 4d). Overall, the La Niña-based streamflow patterns anticipated for this year were realized at more gaging stations in more areas in spring 2000 than in winter, but were not as successful as the historical reliability of La Niña flow patterns would have suggested. Notably, inclusion of recent NPO status in the Dettinger et al. (1999) projections would not have changed those projections.
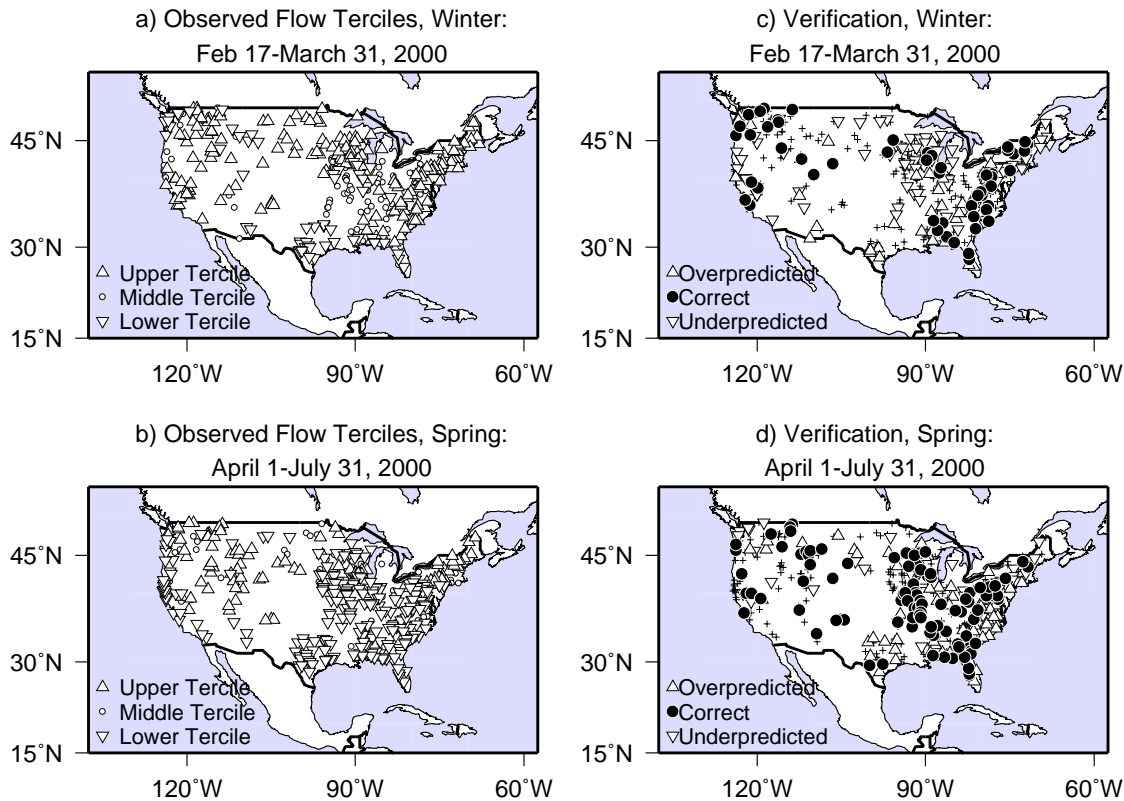
a) Observed Flow Terciles, Winter:
Feb 17-March 31, 2000

c) Verification, Winter:
Feb 17-March 31, 2000

b) Observed Flow Terciles, Spring:
April 1-July 31, 2000

d) Verification, Spring:
April 1-July 31, 2000

Fig . 4 -- Observed seasonal-flow terciles for (a) winter 2000 and (b) spring 2000, and comparisons of observed flow terciles with terciles indicated being as most likely by Dettinger et al. (1999) for (c) winter 2000 and (d) spring 2000. Observations were available between February 17 and July 31, 2000. Only sites that were expected to yield upper- or lower-tercile flows are compared here, in panels (c) and (d). The "observed terciles" are based on terciles of historical flows in the February 17-March 31 and April 1-July 31 periods. Plus ('+') symbols in panels (c) and (d) indicate sites where Dettinger et al. (1999) called for middle-tercile flows or where the largest anomalous probabilities reported there were less than 10%.

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