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Key Points:

- GRACE detected groundwater buildup before the 2011 Missouri River flood
- A quasi-decadal oscillation is found to modulate long-term groundwater changes
- This QDO modulation has a potential for decadal prediction

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The Pacific quasi-decadal oscillation (QDO): An important precursor toward anticipating major flood events in the Missouri River Basin?

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Abstract Measurements taken by the Gravity Recovery and Climate Experiment satellites indicated a continued water storage increase over the Missouri River Basin (MRB) prior to the 2011 flood event. An analysis of the major hydrologic variables in the MRB, i.e., those of soil moisture, streamflow, groundwater storage, and precipitation, show a marked variability at the 10–15 year time scale coincident with the water storage increase. A climate diagnostic analysis was conducted to determine what climate forcing conditions preceded the long-term changes in these variables. It was found that precipitation over the MRB undergoes a profound modulation during the transition points of the Pacific quasi-decadal oscillation and associated teleconnections. The results infer a prominent teleconnection forcing in driving the wet/dry spells in the MRB, and this connection implies persistence of dry conditions for the next 2 to 3 years.

1. Introduction

The 2011 Midwest floods enveloped much of the Missouri and Souris River Basins, causing over US$2 billion worth of damages. Thousands of acres of farmland were submerged displacing roughly 11,000 people. The human toll of the floods also included five fatalities. According to the U.S. Army Corps of Engineers, during May and June 2011, eastern Montana, the western Dakotas, and northern Wyoming experienced particularly heavy rainfall totals. Moreover, in the back-to-back months prior to the flooding, there was a receipt of almost a year's annual runoff in the Missouri River Basin (MRB). Adding to this problem were cooler temperatures throughout the basin, which slowed the melting of the already record high snowpack levels; this meant that much of the snowpack moisture overlapped with the precipitation and so did not allow for either to flow out of the system prior to the inflow of the other. Although prior circumstances as early as February 2011 implied a high probability of such a spring flood, the magnitude of the flood potential was less certain. According to the National Weather Service *NWS-Assessment* [2012], the scale of the event was not fully grasped until heavy rainstorms were realized upstream of the MRB.

In hindsight, the water storage anomaly in the MRB measured by the Gravity Recovery and Climate Experiment (GRACE) twin satellites indicated a persistent buildup of liquid water equivalent (LWE) that started as early as 2009 and peaked in the 2010–2011 winter (Figure 1). The LWE evolution indicates a protracted accumulation of water storage as a precursor to the 2011 floods. Moreover, the geographical distribution of LWE's linear trends from 2003 to 2012 (Figure 1 inset) indicated increasing water storage over the entire MRB.

Given the aforementioned discoveries, we analyzed the major subcomponents of LWE, i.e., soil moisture, streamflow, and groundwater level, in order to identify their roles in the MRB flooding event. A diagnostic analysis was then conducted to determine what climate forcing conditions preceded the long-term changes in LWE. Such climate forcing conditions were found to be oscillatory in nature and potentially predicable, suggesting that flood mitigation techniques could be implemented in the years prior to the extreme precipitation event and the floods that occurred in the MRB as a result.

2. Data

The GRACE observes monthly changes in gravity caused by mass changes of the water layer, whose thickness changes [e.g., *Wahr et al.*, 1998]. The vertical extent of this water thickness is measured in centimeters; the

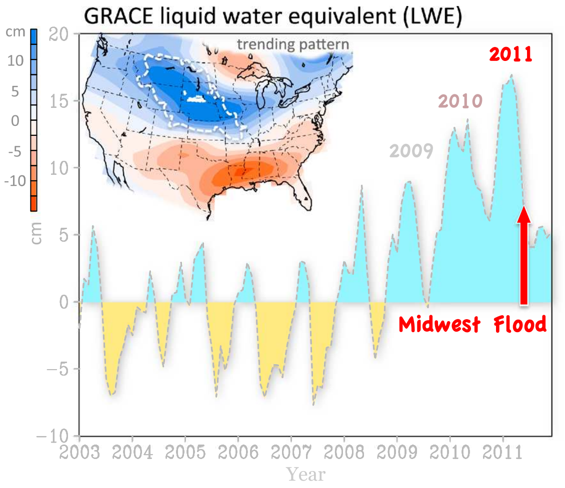


Figure 1. Monthly anomalies of liquid water equivalent (cm) derived from the GRACE averaged within the Missouri River Basin; domain is outlined in the inset map. Blue/yellow areas indicate positive/negative LWE anomalies from the long-term mean. Inset: Geographical distribution of the linear trend in LWE over the period of January 2003 to December 2012, with blue/red areas indicating decreasing/increasing LWE. The white dots in South Dakota indicate the 114 groundwater wells analyzed.

horizontal resolution is 2° longitude × 2° latitude. We utilized the monthly GRACE level 3 LWE, equivalent to the total thickness of water (http://grace.jpl.nasa.gov/data/). Soil moisture data were taken from the North American Land Data Assimilation, which consist of uncoupled models forced with observations. Soil moisture output is measured and assimilated from 0 to 200 cm in depth, and monthly data were used from 1979 to 2011. Streamflow data were obtained from the United States Geological Survey (USGS) stream gage in Sioux City, Iowa, for daily discharge (ft^3/s) from 1928 to 2013 (http://waterdata.usgs.gov/). The upstream of the Sioux City gauge, nearly 89% of the basin, is regulated by the six U.S. Army Corps of Engineers reservoirs within the MRB. Groundwater well data were gathered from the Active Groundwater Level Network (http://groundwaterwatch.usgs.gov/default.asp) operated by the USGS beginning in the 1960s. We analyzed 114 active wells in South Dakota (locations are indicated in Figure 1 inset map); springtime groundwater levels were standardized prior to averaging among the 114 wells. Precipitation data were derived from the station-based, monthly Global Precipitation Climatology Centre data set [*Schneider et al*., 2013]. Atmospheric variables such as wind fields were derived from the National Centers for Environmental Prediction/National Center for Atmospheric Research Global Reanalysis [*Kalnay et al*., 1996] starting in 1948. Sea surface temperature (SST) anomalies were obtained from the Kaplan Extended SST v2 data [*Kaplan et al*., 1998].

3. Results

3.1. Hydrologic Processes

As shown in Figure 2a, soil moisture and streamflow in the MRB reveal marked oscillations alternating at a quasi-decadal frequency. Soil moisture and streamflow both show a prominent peak in the late 1990s and a steep dropoff heading into the early 2000s. A disparity between the two becomes noticeable around 2002, where soil moisture shows a steady increase, and streamflow shows a persistent decline until around 2009. Figure 2b shows the tendency of the groundwater level (i.e., current year minus the previous year) for the depiction of recharge and discharge; this also indicates a robust variability at the decadal time scale and corresponds more strongly with soil moisture than streamflow.

The hydrologic forcing was depicted by the monthly precipitation (Figure 2c) averaged within the MRB boundary (Figure 1 inset) and smoothed by an 18 month running mean (to dampen the seasonal cycle). Fluctuations in the groundwater level tendency are in good agreement with the precipitation, and both time series reveal a significant quasi-decadal variability within the 10–15 year spectral power (not shown). The quasi-decadal variability in the precipitation, reflected by the alternating dry and wet spells, is particularly pronounced after the 1960s. Furthermore, the precipitation oscillation also corresponds well with the soil moisture variation at the decadal time scale.

3.2. Climate Forcing

The unique time scale of 10–15 years revealed from the hydrologic variables echoes an emerging climate mode—the Pacific quasi-decadal oscillation (QDO)—described in a growing number of articles focusing on low-frequency variability in the Pacific SST [e.g., *Allan*, 2000; *Tourre et al*., 2001; *White and Tourre*, 2003; *White and Liu*, 2008; *Wang et al*., 2011]. The Pacific QDO alternates between its warm/cool statuses in the central equatorial Pacific near the Niño 4 region (160°E–150°W, 5°S–5°N). The Pacific QDO features a complete lifecycle with distinctive phases in terms of SST and atmospheric circulation patterns; these include the transition phases

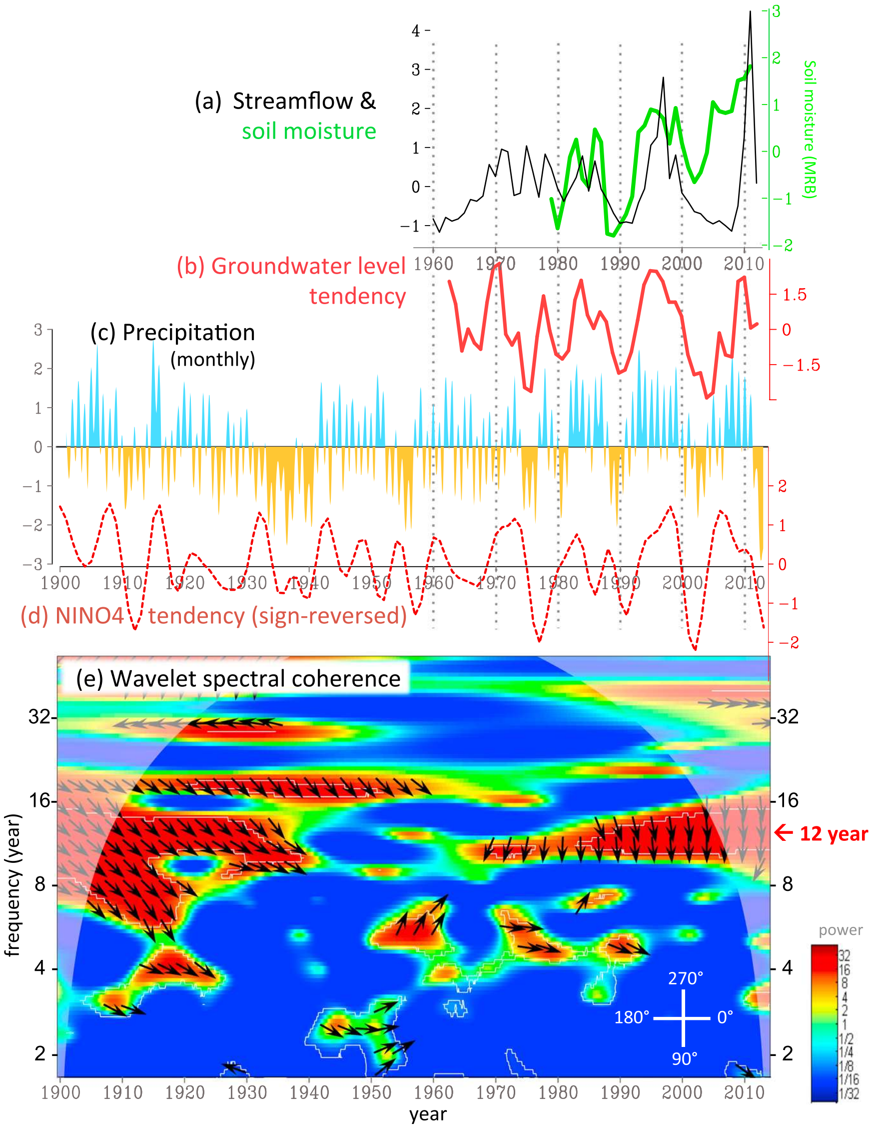


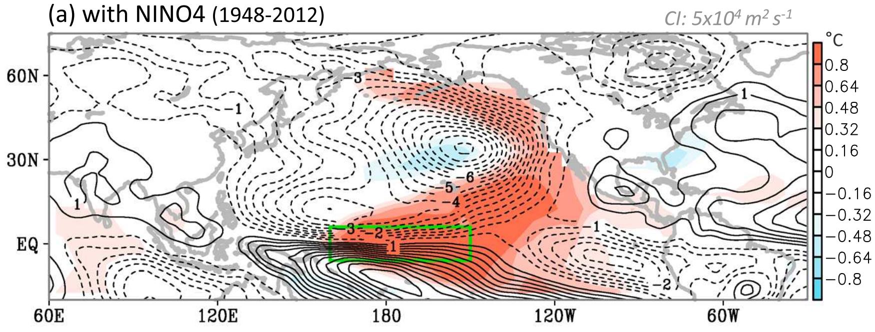
Figure 2. (a) Annual streamflow in Sioux City, Iowa (black) overlaid with soil moisture over the MRB at top 200 cm (green), both time series are standardized. (b) Tendency (time derivative) of spring groundwater level from 114 wells in South Dakota. (c) Monthly precipitation anomalies averaged within the MRB smoothed by a 1-2-1 running mean (in mm/d; blue is positive and orange is negative). (d) Tendency of the Niño 4 index representing the Pacific QDO transitions. (e) Wavelet spectral coherence (shading) and phase difference (vectors) between the monthly precipitation and Niño 4—only the significant spectra (95%; outlined by white contours) are overlaid with phase vectors. A 90° (270°) phase difference means that Niño 4 leads (lags) precipitation by a quarter phase, i.e., 3 years at the 12 year frequency.

in-between the extreme warm and cold [*Wang et al*., 2010a, 2011, 2012]. We used the SST anomalies averaged in the Niño 4 region during the July-to-June annual time period to represent the Pacific QDO, hereafter referred to as “Niño 4.”

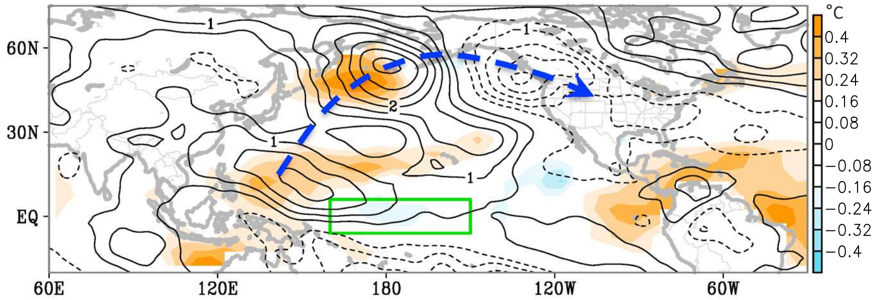
The transition phases of the Pacific QDO can be depicted by the rate of change (or tendency) of the Niño 4; the tendency was smoothed by a 1-2-1 moving average and is plotted in Figure 2d. Here the Niño 4 tendency was reversed in sign (explained next), and it coincides strongly with the decadal wet/dry spells of the MRB precipitation, soil moisture, streamflow, and groundwater level change (Figures 2a–2c). That is, the wet/dry spells experienced throughout the MRB correspond closely with the warm-to-cool/cool-to-warm transition of the Pacific QDO.

To assess the extent to which the Niño 4 and the MRB precipitation are related, we computed the cross wavelet transform and the wavelet coherence using monthly raw data (i.e., without any filtering or smoothing). The

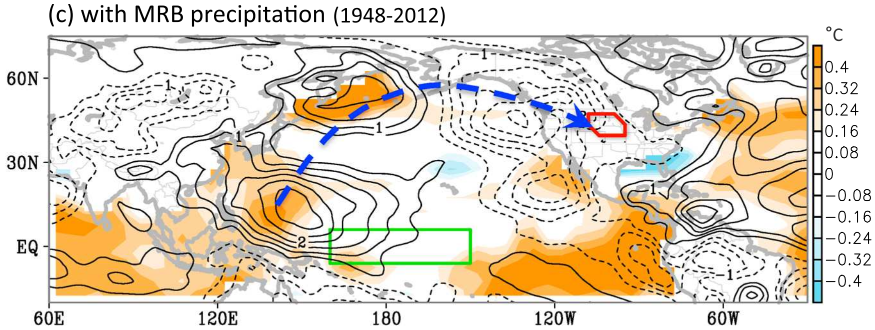
(a) with NINO4 (1948-2012)



(b) with NINO4 **tendency** (1948-2012)



(c) with MRB precipitation (1948-2012)



(d) with **–NAO** (1950-2012)

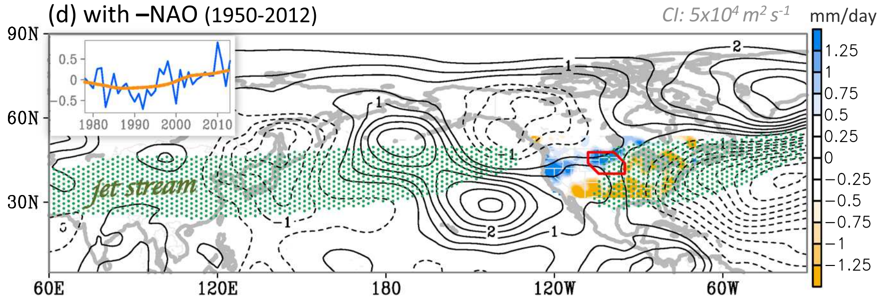


Figure 3. Regression coefficients of annual 850 hPa stream function (contours) and SST anomalies (shadings) regressed, respectively, upon (a) Niño 4, (b) Niño 4 tendency, (c) MRB precipitation, and (d) sign-reversed NAO. Shadings reflect values significant above the 90% level per *t* test. In Figure 3d, the shadings are the precipitation regression, and the green dotted area denotes the jet stream with 200 hPa wind speed greater than 20 m/s. The inset in Figure 3d is the annual NAO index and its 20 year low-passed trend, sign reversed. The blue arrow lines indicate the trans-Pacific short-wave train. The MRB is outlined in Figures 3c and 3d.

wavelet coherence reveals areas of high common spectral power [*Torrence and Webster*, 1999; *Grinsted et al.*, 2004], portrays localized correlation coefficients in time frequency, and uncovers locally phase-locked behavior [*Grinsted et al.*, 2004]. As shown in Figure 2e, the wavelet spectral coherence indicates two features: (a) a concentrated significant spectrum that lies within 8–16 years that is centered at 12 years, reflecting the QDO and (b) within the QDO frequency, the phases are coherent at 90° after 1960 and at ~70° prior to 1940; this result suggests a shared spectral power peaking at 12 years with the maximum (warmest) Niño 4 leading the peak MRB precipitation by a quarter phase (~3 years). Therefore, the statistical analysis is symptomatic of the teleconnection induced during the transition point of the Pacific QDO from one extreme phase to the other.

3.3. Teleconnection Processes

To depict the Pacific QDO's teleconnection pattern, the annual mean 850 hPa stream function (which represents the trajectories of nondivergent low-level flow) and SST anomalies were regressed upon the Niño 4 for the period of 1948–2012. All variables were subjected to a 1-2-1 (year) smoothing prior to the regression, so as to better depict decadal variability (note: the degree of freedom for significance test was thus reduced according to *Bretherton et al*., [1999]). Linear regression function ($X = a + bY$) was applied, respectively, for SST and stream function as X and for the standardized Niño 4 as Y. The annual mean here covered July from the previous year to June, and Niño 4 was standardized.

The resultant regression map (Figure 3a) shows the SST pattern during the warm phase Pacific QDO, which is El Niño-like with widespread warming in the central tropical Pacific. The SST pattern also resembles the central Pacific (CP) type of El Niño [*Ashok et al*., 2007; *Kao and Yu*, 2009] that features distinct decadal variability [*Yu and Kim*, 2010; *Furtado et al*., 2011]. The circulation corresponding to the warm phase QDO reveals a predominant "zonal wave 1" pattern with cyclonic circulations prevailing in the North Pacific. However, the MRB is unaffected by any prominent circulation anomalies. Next, Figure 3b illustrates the 850 hPa circulation and SST anomalies regressed upon the Niño 4 tendency with the sign reversed (i.e., transition of the Pacific QDO). A very different teleconnection structure emerges: The relatively weak, yet statistically significant SST warming in the tropical western Pacific excites a trans-Pacific short-wave train linking to the northwestern U.S. Such a configuration results in an increase in westerly winds toward the upper MRB. *Wang et al*. [2011, 2012] have shown that this short-wave train is maintained both dynamically and thermodynamically and can be excited by tropospheric heating associated with relatively weak SST anomalies in the western Pacific. Such a transition phase teleconnection is embedded in the Pacific QDO's lifecycle, occurring in-between the warm and cool phases. This explains why it is the tendency of the Niño 4 (sign reversed), rather than the Niño 4 itself, that highly correlates with the MRB precipitation.

For further examination, the circulation and SST anomalies were regressed upon the MRB precipitation. As shown in Figure 3c, a trans-Pacific wave train and the cyclonic cell over the upstream MRB appear once more. The SST warming in the western North Pacific is also visible. However, a broad region of positive SST anomalies, not depicted in Figure 3b, appears in the eastern Pacific slightly to the south of the equator; this reflects the existing, yet weak, connection of the El Niño–Southern Oscillation (ENSO) with the MRB [*Mehta et al*., 2012]. *Mo* [2010] has found that the eastern Pacific (EP)-type ENSO events induce a broader circulation anomalies over the U.S. than those produced by the CP-type ENSO, and this expands the precipitation anomalies further north into the MRB. Therefore, the EP SST signals shown in Figure 3c support the ENSO influence on the MRB at interannual time scales.

Finally, we examined any additional climate forcing that potentially made a contribution to the magnitude of the 2011 flood event. One such forcing is the North Atlantic Oscillation (NAO), which affects the U.S. through three routes: (1) a zonal circulation seesaw of the Icelandic low [*Hurrell*, 2003], (2) a teleconnection induced by the NAO's tropical Atlantic SST anomalies [*Kushnir et al*., 2010], and (3) a circumglobal teleconnection confined along the jet stream [*Branstator*, 2002] that could impact North America from the Pacific side [*Wang et al*., 2010b]. As revealed by the stream function and precipitation regressions with the NAO (Figure 3d; sign reversed), a cyclonic circulation develops over western Canada featuring a dimension and location similar to those associated with the MRB precipitation. The cyclonic circulation leads precipitation to increase associated with westerly flows over part of the western U.S. and upper MRB. Meanwhile, a short-wave train develops over the North Pacific along the jet stream (green dotted area), and this echoes the NAO-induced circumglobal teleconnection [*Branstator*, 2002]. An extreme negative phase of the NAO occurred in 2010 and prevailed through 2011 (Figure 3d inset; sign reversed); this contributed to increased cold season precipitation in the northern plains [*Maidens et al*., 2013]. Moreover, the NAO has tended toward more negative phases since the late 1980s, likely in response to the Atlantic multidecadal variability [*Gulev et al*., 2013]. Such a long-term trend also suggests a contribution of the NAO on the recent increase in the MRB precipitation and streamflow.

4. Summary and Discussion

In the MRB, the interannual variability of ENSO explains less than 20% of the precipitation variation while the decadal-scale variability explains over 40% [*Lins and Slack*, 1999; *Cayan et al*., 1998]. The quasi-decadal wet/dry spells in the MRB have long been observed [*Cleaveland and Duvick*, 1992; *Gray et al*., 2004; *McCabe et al*., 2004; *Massei et al*., 2011] and are likewise in the forefront of stakeholders in the industrial and agricultural sectors tasked with the provision of energy and water [*Mehta et al*., 2012]. When abnormal volumes of precipitation persist for longer than usual periods, such as the few years leading up to the 2011 flood, marked increases in water storage and/or flood events of severe magnitude become highly probable. Such processes have been depicted by the GRACE data across the world [*Reager and Famiglietti*, 2009]. In the MRB, the GRACE LWE signals seem to be dominated by soil moisture rather than groundwater level, particularly during short-lived flooding events (Figures 1 and 2). In fact, flooding is more likely to reflect runoff generation due to increased soil moisture rather than groundwater base flow. In this capacity, the GRACE data that summarize both soil moisture and groundwater provide a useful tool to assess and monitor the effective storage capacity in anticipation of major flood events.

There is a greater need today for decadal predictions of hydrometeorology in the MRB [*Mehta et al*., 2012]. The fact that the MRB precipitation anomalies trail behind the warm/cool extremes of the Pacific QDO for a few years, as is identified in this study, means that such a circumstance has potential for prediction of the regional wet/dry cycles. For instance, by applying a similar lead-lag relationship between the Pacific QDO and lake level fluctuations of the Great Salt Lake (GSL) in Utah, *Gillies et al*. [2011] developed a prediction model for the GSL level. By capturing the shared quasi-decadal signals in Niño 4 and precipitation, the model of *Gillies et al*. [2011] was able to predict the lake level out to 8 years and more importantly, the timing of the GSL turnarounds. In this context, developing a similar model in the MRB seems feasible and, if successful, would prove invaluable to provide more timely and effective decision for farmers to take action in the face of impending extreme wet/dry events (e.g., by managing crops and irrigation practices). Additional research to develop such a model could help ameliorate the human and economic shock of extreme wet/dry events. Finally, as can be seen in Figure 2, precipitation and the QDO have reached the peak of its wet cycle and have been heading into a dry cycle, suggestive of prolonged dry conditions for the coming 2 to 3 years.

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