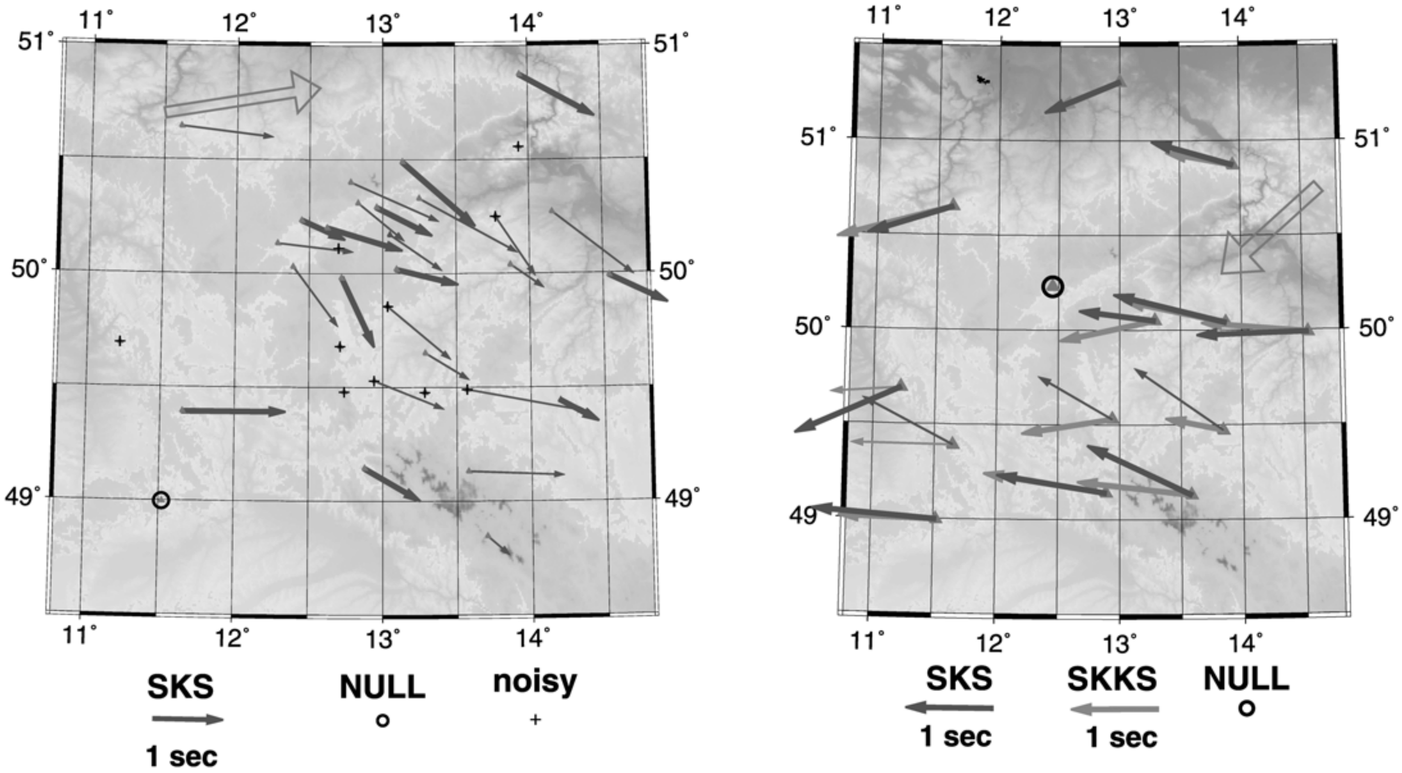

Fig. 3. Fast shear-wave polarization azimuths and delay times of slow shear-waves are shown for two seismic events of 12 October 2002 from Brazil (left) and 12 October 2001 from the Mariana Islands (right), arriving from almost opposite azimuths (large open arrows). The arrows at individual stations point in azimuths of the fast shear-wave polarization vectors evaluated in 3-D. Thin arrows at stations indicate less reliable measurements.

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Accounts from 19th-century Canadian Arctic Explorers' Logs Reflect Present Climate Conditions

PAGES 410, 412

The widely perceived failure of 19th-century expeditions to find and transit the Northwest Passage in the Canadian Arctic is often attributed to extraordinary cold climatic conditions associated with the "Little Ice Age" evident in proxy records. However, examination of 44 explorers' logs for the western Arctic from 1818 to 1910 reveals that climate indicators such as navigability, the distribution and thickness of annual sea ice, monthly surface air temperature, and the onset of melt and freeze were within the present range of variability.

The quest for the Northwest Passage through the Canadian archipelago during the 19th century is frequently seen as a vain and tragic failure. Polar exploration during the Victorian era seems to us today to have been a costly exercise in heroic futility, which in many respects it was. This perspective has been reinforced since the 1970s, when paleoclimate reconstructions based on Arctic ice core stratigraphy appeared to confirm the existence of exceptionally cold conditions consistent with the period glaciologists had termed the "Little Ice Age" (Figure 1a), with temperatures more than one standard deviation colder relative to an early 20th-century mean [*Koerner*, 1977; *Koerner and Fisher*, 1990; *Overpeck et al.*, 1998]. In recent years, the view of the Little Ice Age as a synchronous worldwide and prolonged cold epoch that

By K. Wood and J.E. Overland

ended with modern warming has been questioned [*Bradley and Jones*, 1993; *Jones and Briffa*, 2001; *Ogilvie*, 2001].

This article demonstrates the use of historical instrument and descriptive records to assess the hypothesis that environmental conditions observed by 19th-century explorers in the Canadian archipelago were consistent with a Little Ice Age as evident in proxy records. We find little evidence for extreme cold conditions.

Comparison of Four Climate Indicators

While there is an extensive literature on the history of 19th-century Arctic exploration, surprisingly little use has been made of the detailed scientific and meteorological observations compiled during many expeditions. There were more than seventy expeditions or scientific enterprises of various types dispatched to the Canadian Arctic in the period between 1818 and 1910. From this number, we analyzed 44 original scientific reports and related narratives; many from expeditions spanning several years. The majority of the data come from large naval expeditions that wintered over in the Arctic and had the capacity to support an intensive scientific effort. A table listing the expeditions and data types is located at www.pmel.noaa.gov/arctic/history. The data cover about one-third of the possible number of years depending on data type, and every decade is represented.

Our analysis focuses on four indicators of climatic change: summer sea ice extent, annual sea ice thickness, monthly mean temperature, and the onset of melt and freeze as estimated from daily mean temperature. Historical observations in these four categories were compared with modern reference data; the reference period varied, depending on data availability. Both sea ice extent and the onset of melt and freeze were compared to the 30-year reference period 1971–2000; monthly means are compared to the 50-year period 1951–2000. Modern sea ice thickness records are less continuous, and some terminate in the 1980s; the reference period is therefore based on 19 to 26 years of homogeneous record.

In common with most forms of visual and instrument data, questions regarding the accuracy and reliability of historical observations arise. For example, the measurement of extremely cold winter temperatures was problematic throughout the 19th century. Thermometers were particularly liable to inaccuracy below the freezing point of mercury (-38.8°C). Air temperature measurements in summer are also more likely to reflect cool values, as temperature measurements were generally suspended as soon as ice conditions were favorable enough to permit ships to sail. While a particular historical data series is subject to unknown error, the overall validity of observations is supported by concurrent, independent lines of evidence, which include measurements recorded simultaneously at nearby locations, descriptions of related physical processes, and occasionally, drawings or photos.

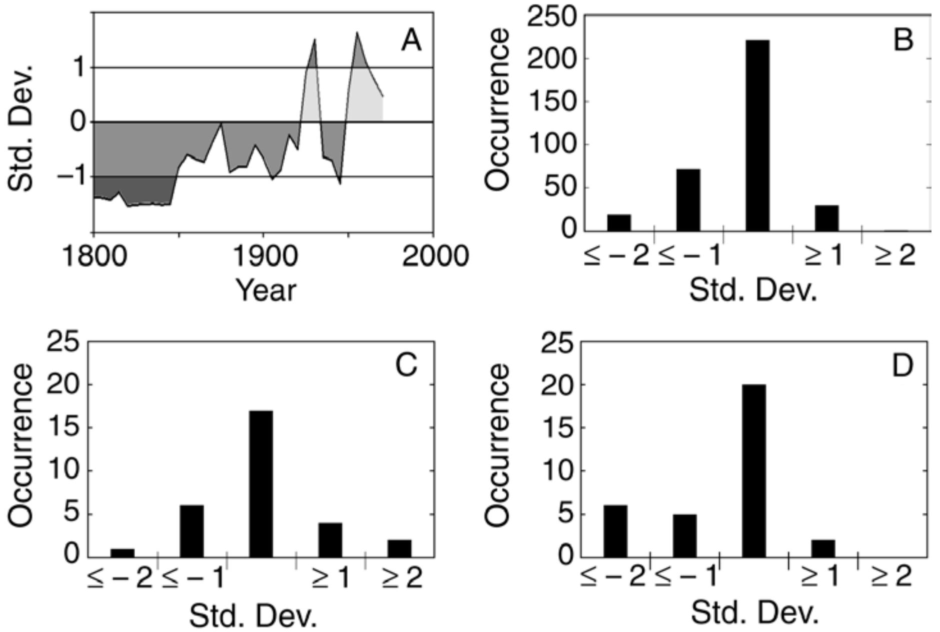


*Fig. 1. (a) Proxy record of standardized summer air temperature variation derived from ice cores taken on Devon Island. This proxy record suggests that a significantly colder climate prevailed in the 19th century. Shading indicates temperatures one standard deviation warmer or colder than average for the reference period 1901–1960 [*Overpeck, 1998*]. (b) Historical monthly mean temperature observations compared to the 20th-century reference period 1951–2000. Sixty-three percent of 343 monthly mean temperatures recorded on 19th-century expeditions between 1819 and 1854 fall within one standard deviation of the reference mean at nearby stations (reference data from Meteorological Service of Canada, 2002; and National Climatic Data Center, 2002). (c) Onset of melt observed by expeditions between 1820 and 1906 expressed as departures from the mean for the reference period 1971–2000. The period of melt transition observed by 19th century explorers is not inconsistent with modern values. (d) Onset of freeze observed between 1819 and 1905 compared to the reference period 1971–2000. The onset of freeze transition is frequently consistent with modern values, but in some cases occurred earlier than usual. The incidence of an early onset of freeze represents the largest departure from present conditions evident in the historical records examined in this study. Melt and freeze transition dates for the reference period 1971–2000 were calculated from temperature data extracted from the Global Daily Climatology Network data base (National Climate Data Center, 2002).*

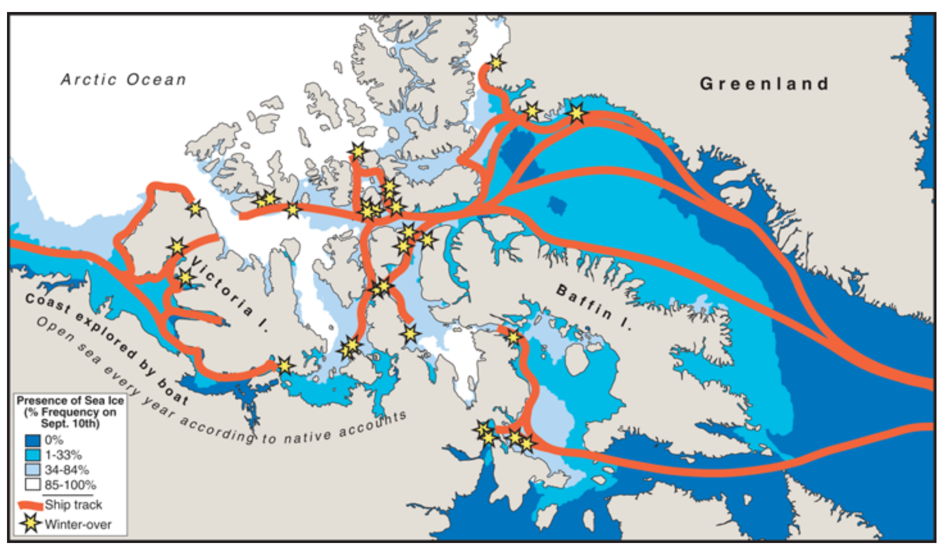


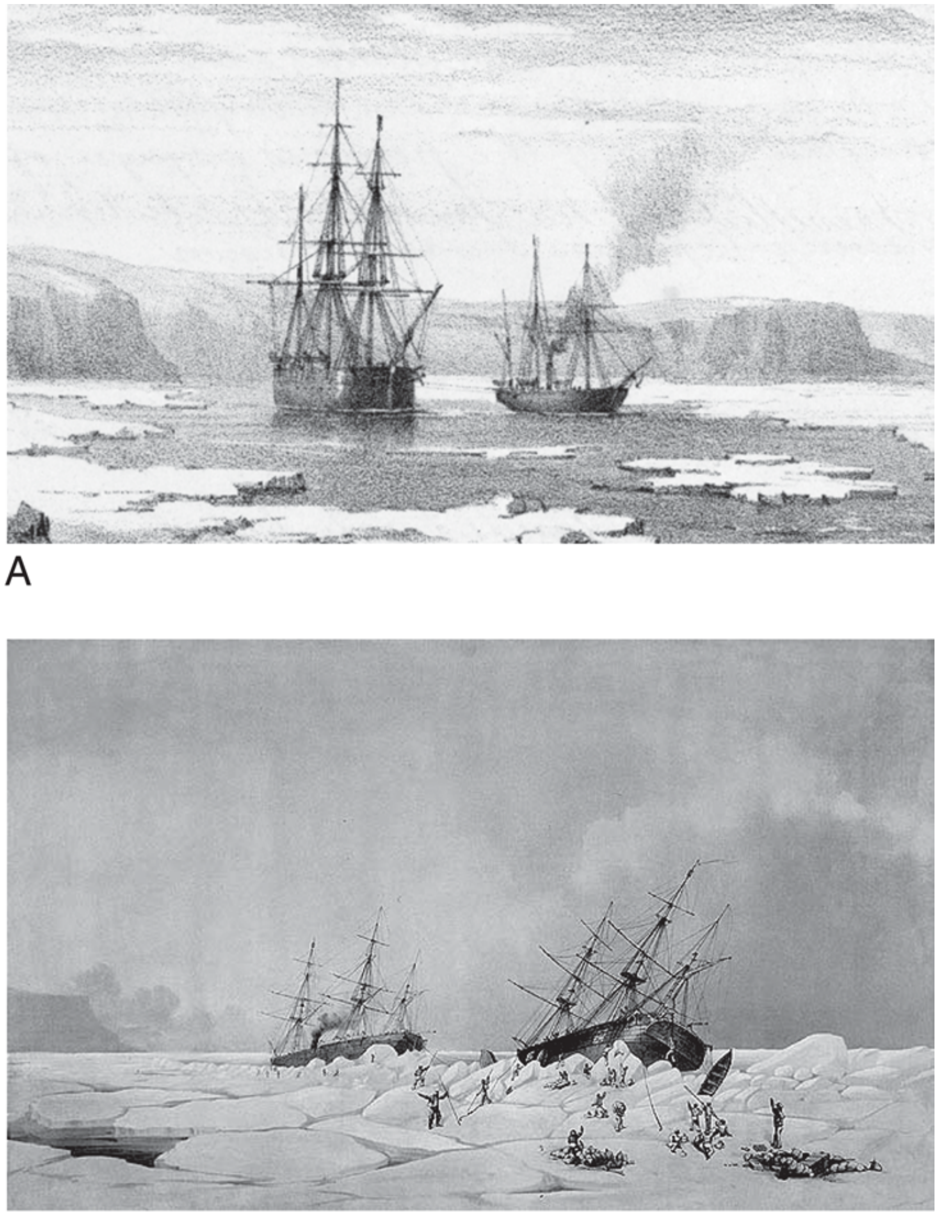
Fig. 2. The ship tracks and winter-over locations of Arctic discovery expeditions from 1818 to 1859 are surprisingly consistent with present sea ice climatology (contours represented by shades of blue). The climatology shown reflects percent frequency of sea ice presence on 10 September which is the usual date of annual ice minimum for the reference period 1971–2000 (Canadian Ice Service, 2002). On a number of occasions, expeditions came within 150 km of completing the Northwest Passage, but even in years with unfavorable ice conditions, most ships were still able to reach comparatively advanced positions within the Canadian archipelago. By 1859, all possible routes comprising the Northwest Passage had been discovered.

The extent of summer sea ice during the 19th century, insofar as it is shown in patterns of navigability inferred from ship tracks, the direct observations of explorers, and a number of native accounts, is remarkably similar to present ice climatology. A chart of northern Canada (Figure 2) shows the routes followed by discovery expeditions and their wintering locations between 1818 and 1859, and also displays the frequency that sea ice has occurred during the recent 30-year reference period 1971–2000. It is perhaps surprising that most of the Northwest Passage was navigated during the 19th century, with expedition ships coming within 150 km of completing the passage on a number of occasions. Most significant is that even in years that were recognized as unfavorable at the time, ships were still able to reach locations that would be consistent with the worst ice conditions that have occurred during the modern reference period. Of 33 expedition or supply ships bound for the western part of Lancaster Sound between 1819 and 1859, only two failed due to unfavorable ice conditions.

Eighteen measurements of maximum annual sea ice thickness were recorded between 1819 and 1876; four of these are incomplete, as they were interrupted before the end of the ice season. The remaining 14 observations had a mean of 215 cm and a maximum of 250 cm. Ice conditions for Resolute Bay, Sachs Harbor, and Mould Bay over 19, 23, and 26 years in the modern era give a mean maximum annual thickness of 199 cm and a mean of the absolute maximum at the three stations of 248 cm. Thus, the historical observations are consistent with 20th-century values.

Thirty-two approximately year-long series of monthly mean surface air temperature series were collected for the years between 1819 and 1854, and compared to the 50-year reference period 1951–2000. Overall, 63% of 343 monthly temperature anomalies fall within one standard deviation of the modern mean (Figure 1b). Even though this period should correspond to one of the colder epochs of the Little Ice Age, only 19 observations approximate record minimum temperatures for the reference period, and 7 of these occurred in 1853. The spring months of April and May appear to be warmer than expected; in these two months, only 10 of 56 measurements were below the reference mean, and none were cooler than one standard deviation below the mean.

Because of the constraining effect of melting ice and snow, variation in the onset of melt and freeze reflect an accurate change in surface air temperature. Melt and freeze transition dates are defined when the 15-day average daily mean temperature rises above or falls below freezing. Sixty-four melt season transition dates were calculated from historical data collected between 1819 and 1906. These dates were compared to modern transition dates 1971–2000. The period of melt transition is not inconsistent with modern values (Figure 1c), and was not delayed as expected, given a markedly cooler climate. Freeze transition is frequently consistent with modern values, but in some cases, occurred earlier than usual (Figure 1d).



A

B

Fig. 3. Explorers encountered both favorable and unfavorable ice conditions. These drawings from the vicinity of Beechey Island illustrate the range of ice conditions in different years. Panel A illustrates the situation of the H.M.S. Resolute *and the steam-tender* Pioneer *on 5 September 1850 [from Facsimile of the Illustrated Arctic News, courtesy of Elmer E. Rasmuson Library, Univ. of Alaska-Fairbanks]. Panel B shows the* H.M.S. Breadalbane *and the steam-tender* Phoenix *beset in pack ice on 21 August 1853. The* Phoenix *escaped, but the* Breadalbane *was caught in a pressure ridge and sank (National Archives of Canada, Accession Number 1989-399-4).*

Explorers Found Both Warm and Cool Conditions

While historical data from voyages of exploration are intermittent, taken as a whole, they provide a valuable perspective on the past climate of the Canadian Arctic. It is clear that the first-hand observations of 19th-century explorers are not consistent with the hypothesized severe conditions of a multi-decadal Little Ice Age. Explorers encountered both warm and cool seasons, and generally typical ice conditions, in comparison to 20th-century norms (Figure 3). The early onset of freeze in some instances represents the greatest apparent departure from present conditions, while the timing of melt transition in the spring showed little change. If there had been a shift in mean summer air temperatures of the magnitude suggested by the melt layer stratigraphy in the Devon Island ice core, indications of colder conditions would have been detected in our analysis.

Neatby [1958] noted that the dangers of the Arctic climate were originally underestimated, because people were prone to reason too much on the basis of a few fortunate results, and neglect the accidental circumstances which produced them. The inverse could equally apply today with respect to our

perceptions regarding the influence of climate upon the history of Arctic exploration. The search for the Northwest Passage in particular was fraught with drama and human tragedy. The notion of a noble quest ultimately doomed to hopeless failure is powerfully evocative, and more so when placed in the context of a Little Ice Age. But it is misleading to state that the Northwest Passage was not found and transited during the 19th century, and that the failure was due to an adverse climate. In fact, all of the potential routes that comprise the Northwest Passage were discovered, and nearly the entire labyrinthine coastline was mapped during this period. And while no ship sailed through the passage in the 19th century, several came within 150 km of doing so, without the aid of an engine, chart, or functioning compass. A similar outcome would be well within the bounds of probability today.

Acknowledgments

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Dramatic End to Galileo Mission to Jupiter

PAGE 411

Galileo, a workhorse NASA spacecraft that overcame numerous technical difficulties to provide important discoveries about the Jovian system, ended its 14-year, 4.6 billion-km mission by plunging into Jupiter's atmosphere on 21 September.

With the 5.3-m-high spacecraft running low on propellant, navigators set its final trajectory to avoid any potential impact or contamination of Europa, a Jovian moon that was found during the mission to likely harbor a sub-surface ocean.

During its 48.2-km-per-second collision course to Jupiter, Galileo collected data closer to the planet than scientists had anticipated, according to Claudia Alexander, Galileo project manager for the Jet Propulsion Laboratory of the California Institute of Technology in Pasadena. JPL has managed the mission for NASA.

Alexander said Galileo may have weathered its penetration of Jupiter's extreme radiation environment better than the spacecraft did during a close pass on its 34th orbit of the planet in November 2002. At that time, Galileo entered an emergency "safe" mode and temporarily ceased science functionality, and scientists had expected that the spacecraft on its final dive would react similarly while racing through the radiation belt.

"What perhaps made the difference is that the spacecraft was moving just a little bit faster on this pass, readying for its final plunge, and the radiation damage is a cumulative effect," she noted. "Once through the radiation belt, there would be no reason not to expect the spacecraft to collect data until impact."

It may be weeks before scientists even can retrieve any final data Galileo collected prior to its vaporization in the Jovian atmosphere. But Alexander anticipates that this data may include new longitudinal information about the planet's radiation belts, as well as data about the ring system, the transition to Jupiter's atmosphere, and Amalthea, the third closest moon to the planet.

During pass 34, Galileo's instruments measured low density for Amalthea and also detected bright objects near the moon. Alexander noted that the two findings suggest that the moon "may be a loosely conglomerated body, somewhat like a comet." A second observation of the moon could help to determine whether these bright objects are still present, and whether they may constitute a ring of large debris around Jupiter coming from Amalthea.

Any final science data would add to a string of startling discoveries of the Jovian system by Galileo. These findings include evidence that the moons Europa, Ganymede, and Callisto have a liquid-saltwater layer and may also possess a surface-bound exosphere. Galileo also found that Io's volcanic activity may be 100 times greater than that of Earth, and that the moon's flux tubes magnetically connect it to Jupiter.

Also, Ganymede was found to be the first moon known to possess a magnetic field, and the mission provided insights about Jupiter's magnetosphere, ammonia clouds, and other atmospheric elements and properties. Among other accomplishments, Galileo also made the first flyby of an asteroid, took the only direct observation of Comet Shoemaker-Levy 9's impact into Jupiter's atmosphere, and was the first spacecraft to orbit an outer planet and deploy a probe into an outer planet's atmosphere.

But Michael Belton, team leader for the Galileo Solid State Imaging Team and emeritus astronomer with the National Optical Astronomy Observatories in Tucson, Arizona, said that Europa "was the star of the show." He said that Galileo's discoveries transformed scientific understanding of Europa from "an icy, fuzzy ball" to a complex body.

"By proving there is a deep liquid ocean underneath the ice cap transforms [Europa] from a mere moon to a prime candidate for extraterrestrial life," he said.

The $1.39-billion Galileo mission, launched on 18 October 1989, arrived into orbit around Jupiter on 7 December 1995. Although plans originally called for the spacecraft to orbit the planet 11 times during a 23-month period, the mission was extended twice. The mission also overcame significant technical difficulties, including the failure of the spacecraft's High Gain Antenna and tape recorder problems.

Alexander noted, "A lot of ingenuity was poured into the mission to salvage the science."

She indicated that the mood among scientists and engineers at JPL during Galileo's plunge into Jupiter's atmosphere was sad and reminiscent. But she said scientists also were hopeful and forward-thinking. A follow-on Jupiter Icy Moons Orbiter mission is expected to launch in 2012–2014, and arrive in orbit around Jupiter by the end of that decade.

Alexander said, "It was fitting that the [Galileo] mission come to an end. We discovered an ocean, so the mission will always be an historic one. However, the technology was very much 1970s technology, and we have moved so far ahead now."

—Randy Showstack, Staff Writer