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Author

WILSON, Jordan

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Supercomputing and Energy in China: How Investment in HPC Affects Oil Security

Jordan WILSON

Researcher, Study of Innovation and Technology in China Project
UC Institute on Global Conflict and Cooperation

China has raced to the forefront of the global high performance computing (HPC) industry over the past decade, moving from placing no computers on the industry's "Top500" list in June 2001 to 63 today, second only to the United States.¹ China topped the list for the first time in 2010 with its domestic-made Tianhe-1A machine, and now holds the lead again with the Tianhe-2, having rolled it out two years earlier than expected in June 2013.² China reportedly has plans to achieve HPC's next milestone, exascale-speed computing, in 2020, two years before projections for the industry in the United States.³

While China's supercomputers continue to impress with their sheer computing power, doubts exist as to whether they are being fully used. Worldwide these multimillion-dollar machines are put to use for a wide range of applications, including nuclear weapons simulations and stockpile management, intelligence analysis, climate prediction, plasma physics, vehicle and aircraft design, computational biology, earthquake simulations, geophysical exploration, astrophysics, materials science, and human/organizational systems studies.⁴ In China the impact is much less clear, as applications lag behind hardware and many supercomputers reportedly sit idle.⁵ Are China's aggressive efforts in HPC an overreach analogous to its ghost cities and extravagant infrastructure projects, or is there evidence of meaningful development in HPC applications as well?

This analysis will focus on the application of HPC to oil exploration in particular to examine China's progress in supercomputing and the impact it is making. From the earliest days of supercomputing oil exploration has been a sector that has exhibited a high demand for HPC, with developments in geophysical data processing software closely

1 Louisa Lim, "China's Supercomputing Goal: From 'Zero to Hero'," NPR, August 2, 2011, accessed November 25, 2013, <http://www.npr.org/2011/08/02/138901851/chinas-supercomputing-goal-from-zero-to-hero>; "List Statistics," Top500 Computer Sites website, accessed December 2, 2013, <http://www.top500.org/statistics/list/>.

2 "China's Tianhe-2 Supercomputer Takes No. 1 Ranking on 41st TOP500 List," Top500 Computer Sites website, June 17, 2013, accessed November 25, 2013, <http://www.top500.org/blog/lists/2013/06/press-release/>.

3 U.S. Department of Energy, "Department of Energy Exascale Strategy," June 2013 report to Congress.

4 Susan L. Graham, Marc Snir, and Cynthia A. Patterson, eds., *Getting Up to Speed: The Future of Supercomputing* (Washington, DC: National Academies Press, 2004), 71, accessed December 9, 2013, http://www.nap.edu/openbook.php?record_id=11148&page=71.

5 Stephen Chen, "World's Fastest Computer, Tianhe-2, Might Get Very Little Use," *South China Morning Post*, June 20, 2013, accessed December 9, 2013, <http://www.scmp.com/news/china/article/1264529/worlds-fastest-computer-tianhe-2-might-get-very-little-use>

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tracking developments in HPC architecture.⁶ This field is also directly relevant to China's energy security challenge and thus touches on national security concerns, making it a strong candidate for potential utilization of HPC.

The Need for HPC in Oil Exploration

To state China's energy security challenge briefly, an oil deficit of 6 million barrels per day and projected dependence on foreign oil imports of 60 percent by 2020 and 75 percent by 2035 has raised concerns within China's leadership that vulnerability to international oil price fluctuations could be costly to its economy.⁷ China's national oil companies (NOCs), China National Petroleum Corporation (CNPC), China Petroleum and Chemical Corporation (Sinopec), and China National Offshore Oil Corporation (CNOOC), are important tools within China's oil sector for addressing these concerns.⁸ One key government strategy is to support these NOCs' investments in international oil exploration and development projects, seeking to lock in energy supplies around the world to balance against the economic risks of the world market.⁹ Another is to squeeze as much remaining product out of China's mature and declining domestic oil fields as possible, as well as to focus new efforts on developing untapped domestic reserves in the western provinces and offshore.¹⁰ For all of these efforts it is essential that China's NOCs maintain high capabilities in oil exploration.

Supercomputers assist in oil exploration in three primary ways: seismic data processing, reservoir simulation, and computation visualization.¹¹ Of these, seismic data processing is the most computationally intensive.¹² Air gun arrays with hundreds of thousands of guns are used to fire shock waves into the ground to obtain readings on seismic data, each gun containing hundreds to thousands of "geophones," and each "geophone" collecting data from 3,000–6,000 sampling points.¹³ This yields an astronomical amount of data, often reaching into the hundreds of terabytes, which major oil exploration companies around the world rely on HPC to process.¹⁴ With a supercomputer, data from these surveys can be combined to produce three-dimensional maps of the subsurface, helping to identify potential drilling locations.¹⁵ To place these technical advantages in economic terms, faster computing can change an oil company's cost-benefit calculations by allowing it to process data more quickly, create a more accurate model with fewer assumptions, and monitor changes in a site over time, "de-risking" the process and making drilling in

6 Sun Ninghui, David Kahaner, and Debbie Chen, "High-Performance Computing in China: Research Applications," *International Journal of High Performance Computing Application* 24, no. 4 (2010): 386, doi:10.1177/1094342010381800.

7 U.S. Energy Information Administration, "China Analysis Brief," last updated April 22, 2013, accessed November 25, 2013, <http://www.eia.gov/countries/cab.cfm?fips=CH>; Erica Strecker Downs, *China's Quest for Energy Security* (Santa Monica, CA: RAND Project Air Force, 2003), accessed December 10, 2013, http://www.rand.org/pubs/monograph_reports/MR1244.html; U.S. Energy Information Administration, "China Analysis Brief"; Bruce Blair, Chen Yali, and Eric Hagt, "The Oil Weapon: Myth of China's Vulnerability," *China Security*, accessed March 17, 2013, http://www.chinasecurity.us/index.php?option=com_content&view=article&id=239; Craig Stephen, "Is High Oil Price Behind China's Slowdown," April 15, 2012, accessed November 25, 2013, <http://www.marketwatch.com/story/is-high-oil-price-behind-chinas-slowdown-2012-04-15>.

8 U.S. Energy Information Administration, "China Analysis Brief."

9 Downs, *China's Quest for Energy Security*; Cheryl Canning, "Pursuit of the Pariah: Iran, Sudan, and Myanmar in China's Energy Security Strategy," *Security Challenges* 3, no. 1 (2007): 50.

10 Sigfrido Burgos Caceres and Sophal Ear, *The Hungry Dragon: How China's Resource Quest is Reshaping the World* (New York: Routledge, 2013), 139; U.S. Energy Information Administration, "China Analysis Brief."

11 Sun, Kahaner, and Chen, "High-Performance Computing in China," 387.

12 Ibid.

13 "HPC in China, Part 2: Applications and Trends," Asian Technology Information Program website, March 31, 2010, accessed October 1, 2013, <http://www.atip.org/atip-publications/atip-reports/2010/7876-atip10-007-hpc-in-china-part-two-applications-and-trends.html>.

14 Sun, Kahaner, and Chen, "High-Performance Computing in China," 387; John Kemp, "Super-computers and the Hunt for Oil," *Reuters*, May 7, 2013, accessed October 1, 2013, <http://www.reuters.com/article/2013/05/07/column-kemp-oil-supercomputers-idUSL6N-0DO3YK20130507>.

15 Kemp, "Super-computers and the Hunt for Oil."

complex environments more affordable.¹⁶ This is projected to become increasingly important as easily accessible fields become scarcer and the risk of miscalculating drill sites increases, a concern that has sparked competition among top Western oil companies to obtain the fastest supercomputers.¹⁷

HPC and Oil Exploration in China

China will be especially impacted by the growing scarcity of easily accessible reserves, as journals inside the country describe its domestic drilling environment as greatly complex and lament that exploration conditions there are worsening.¹⁸ In fact, one publication describes the demand in China for HPC in geophysics as “boundless.”¹⁹ Data from the China Software Industry Association’s annual “Top100” list of the fastest machines in China shows that exploratory geophysics has been one of China’s greatest areas of HPC application. From 2005 to 2010 geophysics as a designated application area held the largest share of computers on the list, peaking at 35 machines in 2008.²⁰ Other sources state that Chinese oil companies now all use parallel technology—the simultaneous usage of multiple computing resources to solve problems—to conduct more complex explorations, and that cluster computing, using a collection of computers on a network to form one single computing resource, is in particular becoming increasingly cost-effective and useful.²¹ One CNPC document states that China has become one of the world’s most powerful and competitive states in processing seismic data, due to its increased usage of computer clusters.²²

The journal *Scientific Computing* describes the petroleum industry in China as having “long-standing HPC credentials,” and China’s timeline of supercomputing advancements indeed shows a long history of applying new machines to geophysics uses.²³ Between 1956 and 1990 China invested in HPC for strategic reasons, with oil exploration one of the key strategic sectors it was intended to support.²⁴ During this time some Chinese supercomputers were specifically designated for oil exploration data processing, with the last of these, the KJ8920, being produced in 1991.²⁵ Since this period both hardware and software markets have opened to international vendors, and the

16 Emily Pickrell, “Supercomputers Give Oil Explorers a Sharper View Underground,” *Fuel Fix*, March 28, 2013, accessed October 1, 2013, <http://fuelfix.com/blog/2013/03/28/supercomputers-have-opened-up-new-reservoir-plays/>; Wulf Massell, “Computing Models Advancing as Oil and Gas Industry Demands Change,” Cray Inc., September 17, 2013, accessed October 1, 2013, <http://blog.cray.com/?p=6299>; Kemp, “Super-computers and the Hunt for Oil.”

17 Kemp, “Super-computers and the Hunt for Oil”; Pickrell, “Supercomputers Give Oil Explorers a Sharper View Underground.”

18 Huang Yi, Shi Xueming, Fan Jianhe, and Hu Wenbao, “并行计算技术及其在勘探地球物理学中的现状与展望 [Review on Parallel Computing and its Application in Exploration Geophysics],” *地球物理学进展 [Progress in Geophysics]* 25, no. 2 (2010), http://d.wanfangdata.com.cn/Periodical_dqwlxjz201002038.aspx; Zhao Gaishan, “地球物理高性能计算的新选择: GPU计算术 [New Alternative to Geophysical High Performance Computing: GPU Computing],” *勘探地球物理学进展 [Progress in Exploration Geophysics]* 30, no. 5 (2007), http://d.wanfangdata.com.cn/Periodical_ktdqwlxjz200705016.aspx.

19 Zhao, “New Alternative to Geophysical High Performance Computing.”

20 “评测公告 [Ranking Announcements],” 中国软件行业协会数学软件分会 [China Software Industry Association Branch of Mathematical Software], <http://www.samss.org.cn/sites/shuxue/pcgg.jsp>; Yuan Guoying and Yan Jiuyuan, “高性能计算: 2013年中国高性能计算机性能TOP100排行榜 [High Performance Computing: 2013 Top100 List of High Performance Computing Performance in China],” slideshow by HPC Top100, October 29, 2013, accessed November 25, 2013, http://wenku.it168.com/d_001292503.shtml.

21 Blaise Barney, “Introduction to Parallel Computing,” last updated July 15, 2013, accessed December 13, 2013, https://computing.llnl.gov/tutorials/parallel_comp/#Whatis; Huang Yi, Shi Xueming, Fan Jianhe, and Hu Wenbao, “并行计算技术及其在勘探地球物理学中的现状与展望 [Review on Parallel Computing and its Application in Exploration Geophysics],” *地球物理学进展 [Progress in Geophysics]* 25, no. 2 (2010), http://d.wanfangdata.com.cn/Periodical_dqwlxjz201002038.aspx; Victor Hazelwood, “Cluster Computing: A Survey and Tutorial,” accessed December 12, 2013, http://www.sdsc.edu/~victor/Projects/NQE/SysAdmin/SysAdmin_Batch.html; Zhao Gaishan and Bao Honglin, “集群计算技术及其在石油工业中的应用 [Cluster Computing Technique and its Application to the Petroleum Industry],” *石油物探 [Geophysical Prospecting for Petroleum]* 40, no. 3 (2001), http://d.wanfangdata.com.cn/Periodical_sywt200103018.aspx.

22 “地震资料数字处理需要高性能计算机” [Seismic Data Processing Requires High Performance Computing], 中国石油 [China National Petroleum Corporation], December 29, 2008, accessed December 10, 2013, http://www.cnpc.com.cn/News/zzxw/sybk/syys/syjc-zs/200812/20081229_C327714.shtml?COLLCC=1195937284&.

23 Steve Conway, “Where Does Asia Stand?” *Scientific Computing*, March 19, 2011, accessed November 1, 2013, <http://www.scientific-computing.com/articles/2011/05/where-does-asia-stand#.UqpET9GA1aE>.

24 Sun, Kahaner, and Chen, “High-Performance Computing in China,” 367.

25 Ibid.

development of domestic software for petroleum applications has continued. For example, when Western vendors in 2002 placed export controls on the state-of-the-art OMEGA and GeoCluster seismic data processing software products that China's NOCs were using, CNPC's subsidiary oil exploration company, the Bureau of Geophysical Prospecting (BGP), immediately invested in developing its own viable system, coming out with GeoEast in 2005.²⁶ Other examples include iCluster, seismic data processing software developed by Sinopec; PRIS, a reservoir simulation software developed by the Chinese Academy of Science's Institute of Software; and PRBS, a reservoir simulation software developed by a CNPC subsidiary.²⁷ Looking forward, Chinese petroleum users are said to "widely anticipate" the development of more effective HPC systems to meet their expanding demands.²⁸

Have China's NOCs Been Impacted by HPC Investment?

In recent years, the number of geophysics-dedicated machines on the "Top100" list has seen a surprising decline, with only three to five such computers on the list in the years 2011 to 2013.²⁹ This could be due to the widening use of HPC in China in general, but another potential factor could be the strategic investments in the HPC industry made by China's government. There are three potential avenues through which this government-led effort and resulting expansion of China's capabilities in HPC could be affecting the petroleum industry.

First, the government's efforts could, by fostering China's domestic HPC industry overall, benefit NOCs by providing them with less expensive or more capable machines. There is no evidence for such an impact, however. NOCs are uninhibited in their ability to purchase viable HPC systems on the international market and have typically done so; 75 percent of the systems owned by oil companies on the "Top100" list over the past five years have been bought from IBM, HP, or Dell.³⁰ Thus whatever domestic industry improvements the government may intend, oil companies still apparently see foreign machines as preferable.

Second, state investment could, by fostering the domestic HPC industry, serve to fortify China's petroleum companies against future loss of access to international vendors, as occurred in the case of the software export controls placed on OMEGA and GeoCluster.³¹ This concern is prevalent in China's overall push for indigenous innovation in HPC, particularly on the software side, and Chinese NOCs did benefit from domestic assistance in the development of at least two geophysics applications: from Inspur on GeoEast and from the Chinese Academy of Sciences on PRIS.³² But this would not seem to be a significant concern of China's oil industry. NOCs in general still primarily elect to use commercial software products from international vendors and the software suites that originally raised apprehensions, OMEGA and GeoCluster, now appear to be back on the market and in use by CNPC.³³ China's current weakness in applications relative to hardware means its ability to assist the petroleum industry in this area is limited.

A final potential avenue of impact would be China's national supercomputing centers (NSCCs), funded by state investment at both local and national levels and equipped with world-class machines. Six major centers are currently relevant for industry users: NSCC-Tianjin has a Tianhe-1A computer, NSCC-Changsha has another version

26 Ibid., 384.

27 Ibid., 367.

28 "评测公告 [Ranking Announcements]."

29 Ibid.

30 Ibid.

31 Sun, Kahaner, and Chen, "High-Performance Computing in China," 384.

32 Author interview with expert on high-performance computing, China, November 21, 2013; Dong Zhang, "Inspur and HPC," presentation by Inspur Group, 2013, accessed December 2, 2013, http://scc.acad.bg/ncsa/documentation/First%20Europa-China%20Conference%202013/EU-China_Talks_Videos/Mr.%20Dong%20Zhang%20-%20INSUR%20and%20HPC/Presentation_DongZhang.pdf; Sun, Kahaner, and Chen, "High-Performance Computing in China," 384.

33 Sun, Kahaner, and Chen, "High-Performance Computing in China," 387; "Processing," BGP Inc., China National Petroleum Corporation website, updated 2013, accessed December 2, 2013, <http://www.bgp.com.cn/Service/Processing.html>.

of the Tianhe-1A, NSCC-Jinan has the Sunway Bluelight, NSCC-Shenzhen has the Dawning Nebulae, NSCC-Guangzhou currently houses a system based on the Tianhe-1A and will soon house the Tianhe-2, and the Shanghai Supercomputing Center (relevant though not technically an NSCC) has a Dawning 5000A.³⁴ For each NSCC, information on users and projects is scarce. Nonetheless a study of documents published and achievements advertised by these centers yields a rough picture of their utilization by NOCs. For Tianjin, oil exploration is referenced as a priority in the center's efforts to spur economic development and develop strategic industries.³⁵ Jinan's 2013 "Project Application Guide" identifies petroleum exploration as one of this year's emphasized application areas to support.³⁶ Geophysics has been referenced as an area of application for Shanghai, and it is known that in 2005 Sinopec's research institute in Nanjing was using the center's Dawning 4000A.³⁷ An interview with an application support specialist from Inspur indicated that petroleum applications will be run on Tianhe-2 in Guangzhou.³⁸ Geophysics is briefly mentioned as an application area for Shenzhen on its website, while for Changsha no reference can be found.³⁹

Key Advantages Provided by National Supercomputing Centers

While data on specific applications run at China's NSCCs is largely unavailable, there is a relative wealth of information on NOC usage of the Tianhe-1A at NSCC-Tianjin that can serve as a case study for this analysis. This data is especially telling, as the Tianhe-1A was the most powerful computer in the country prior to the installation of the Tianhe-2 and was deployed in the center closest to CNPC, Sinopec, and CNOOC's Beijing headquarters, in a city which houses several of their research institutes and subsidiaries, and in proximity to major domestic oilfields, making it a likely candidate for NOCs to utilize.⁴⁰ An article written by experts at the National University of Defense Technology (NUDT), the organization responsible for the design of the system, reports that

34 "HPC China 2012," Asian Technology Information Program website, accessed October 1, 2013, <http://www.atip.org/atip-publications/atip-reports/2013/8146-atip13-005-hpc-china-2012.html>; "Top500 List: November 2013," Top500 Computer Sites, November 2013, accessed December 11, 2013, <http://www.top500.org/list/2013/11/>.

35 "国家超级计算天津中心用户已超过400家 [National Supercomputing Center in Tianjin Has More than 400 Users]," 中华人民共和国工业和信息化部 [Ministry of Industry and Information Technology of the People's Republic of China] website, May 14, 2013, accessed October 1, 2013, <http://www.miit.gov.cn/n11293472/n11293832/n11293907/n11368277/15407340.html>.

36 "国家超级计算济南中心超级计算专项(2013)项目申请指南 [National Supercomputing Center Jinan 2013 Special Project Application Guide]," 山东省科学院 [Shandong Academy of Sciences] website, updated 2006, accessed December 10, 2013, <http://www.sdas.org/tzgg/4574.htm>.

37 Yu Li, "世界各地超级计算中心的发展概况 [Overview of the Development of Supercomputing Centers Around the World]," ScienceNet (blog), February 27, 2013 (3:06 p.m.), accessed October 1, 2013, <http://blog.sciencenet.cn/blog-449420-665595.html>; Kong Xiangning, Fang Wubao, Zhao Gaishan, Yuan Liansheng, "曙光4000A上的三维叠前深度偏移并行计算 [3D Pre-Stack Depth Migration Parallel Computing on the Dawning 4000A]," 中国石化石油勘探开发研究院南京石油物探研究所, 南京, 210014 [Sinopec Nanjing Research Institute of Petroleum Exploration and Development, Institute of Petroleum Geophysics, Nanjing, 210014], June 30, 2009, accessed October 1, 2013, http://d.wanfangdata.com.cn/Conference_7055239.aspx.

38 Author interview with application support specialist at Inspur, November 19, 2013.

39 "High Performance Computing Services," 国家超级计算机深圳中心 [Shenzhen National Supercomputing Center] website, updated 2013, accessed October 1, 2013, <http://www.nscsz.gov.cn/hpc>.

40 "CNPC Subsidiaries," in the 2003 annual report of the China National Petroleum Corporation, accessed December 10, 2013, http://www.cnpc.com.cn/Resource/english/images1/pdf/03Annualreport/CNPC_Subsidiaries.pdf; "About Sinopec: Subsidiaries," Sinopec Corp. website, updated 2013, accessed December 10, 2013, http://english.sinopec.com/about_sinopec/subsidiaries/; "CNOOC Headquarters," Kohn Pedersen Fox website, updated 2013, accessed December 10, 2013, <http://kpf.com/project.asp?T=4&ID=17>; "CNOOC Builds Tianjin R&D Base," China National Offshore Oil Corporation website, August 24, 2010, accessed December 10, 2013, <http://www.cnooc.com.cn/data/html/news/2010-08-24/english/301632.html>; "Dagang Oilfield," Oil China Company website, last updated 2004, accessed December 10, 2013, <http://www.oilchina.com/eng/Service-Center/oilfields/Dagang.htm>; "CNOOC Aims for Bohai Bay to Be China's Second Largest Oil Field," Tianjin Commission of Commerce website, October 16, 2007, accessed December 10, 2013, <http://www.tjcoc.gov.cn/index.php?m=content&c=index&a=show&catid=202&id=3392>.

while petroleum companies made up only 2 percent of the Tianhe-1A's users in 2010 and 2011, they accounted for 40 percent of its usage.⁴¹ A petroleum exploration data processing platform is one of five such application platforms that have been designed around the machine, further demonstrating the importance of this application at the center.⁴² BGP announced in 2011 that it would set up a geophysical data processing center in Tianjin that would partner with NSCC-Tianjin and the Tianhe-1A, and according to the center's website has been able to achieve good processing results running its GeoEast software on the machine.⁴³ Sinopec's Nanjing research institute has also partnered with the center and successfully run the company's proprietary iCluster software on the Tianhe-1A.⁴⁴ Finally, it is worth noting that the sharp decline in the share of geophysics machines on China's annual "Top100" lists coincided with the introduction of the Tianhe-1A in 2010, dropping to 16 machines that year and three, five, and four the following years.⁴⁵ The Tianhe-1A could thus have reduced the need for NOCs to buy their own HPC resources, although more complete data on purchases must still be gathered to confirm this.

The services offered by NSCC-Tianjin provide several key advantages to NOCs. The center is aimed at fostering broader economic growth, scientific advancement, and industry support, under the sponsorship of China's Ministry of Science and Technology, Ministry of Finance, Ministry of Industry and Information Technology, and the local Tianjin government.⁴⁶ This appears to benefit the oil industry in three ways. First, although NOC users have the ability to accumulate their own HPC infrastructure, the NSCC machines are significantly faster.⁴⁷ When CNPC first ran a task on a Tianhe-1A in 2011, for example, it took only 16 hours for the supercomputer to process the data, 30 times faster than any machine CNPC had available.⁴⁸ Second, using national supercomputing centers helps companies avoid the high maintenance costs and inefficiencies due to low usage rates they would incur by making such massive investments themselves.⁴⁹ BGP, for example, seeks to double its internal computing capacity every 18 months but has faced power consumption, space, load-bearing, and cooling challenges.⁵⁰ Its partnership with NSCC-Tianjin aims to improve data processing efficiency and industrial competitiveness by utilizing the Tianhe-1A.⁵¹ Experts from NUDT state that Tianhe-1A saved 100 million RMB for all its users (beyond just NOCs) in its first year, by eliminating costs of infrastructure upgrades or investments in hardware or software.⁵² A final way NOCs are advantaged in using the center is that they likely receive a discount for doing so. This observation is based on the fact that the more established Shanghai Supercomputing Center charges a higher rate for core hours while newer centers, such as Tianjin, charge as low as half Shanghai's price to boost interest in their often underused machines.⁵³ Faster machines, reduced overhead costs, and likely subsidization are thus all benefits NSCC-Tianjin can offer to energy companies in fulfillment of China's national HPC strategy. Liu Guangming, NSCC-Tianjin's director, stated in an interview with NPR that through its partnership with CNPC the center has "made a huge contribution to our country's energy development."⁵⁴

41 Xiangke Liao, Yutong Lu, and Min Xie, "Tianhe-1A Supercomputer: System and Application," in *Contemporary High Performance Computing: From Petascale to Exascale*, ed. Jeffrey S. Vetter (Boca Raton, FL: CRC Press, 2013), 501.

42 Ibid.

43 "TEDA Cloud Computing," Tianjin Economic-Technological Development Area Administrative Commission website, updated 2008, accessed October 1, 2013, http://www.teda.gov.cn/html/teda_index2011/SDJD/yjs/yjs.html; "Petroleum Exploration," National Supercomputer Center in Tianjin website, updated 2009, accessed October 1, 2013, http://www.nsc-tj.gov.cn/areas/areas_1.asp.

44 "Petroleum Exploration."

45 "评测公告" [Ranking Announcements]."

46 Meng Xiang Fei, "Application and Research of National Supercomputer Center in Tianjin," presentation to Asia Supercomputer Community, accessed December 2, 2013, <http://www.asc-events.org/13en/To%20web/NSCC-TJ%20application%20and%20research.pdf>.

47 Sun, Kahaner, and Chen, "High-Performance Computing in China," 374.

48 Zhou Chang, "Bigger, Faster, More Efficient," *China Today*, March 1, 2013, accessed November 25, 2013, http://www.chinatoday.com.cn/english/report/2013-03/01/content_526066_2.htm.

49 Ibid.

50 Sun, Kahaner, and Chen, "High-Performance Computing in China," 386.

51 "TEDA Cloud Computing."

52 Liao, Lu, and Xie, "Tianhe-1A Supercomputer," 502.

53 Interview with scientific computing engineer, Shanghai Supercomputer Center, November 19, 2013.

54 Lim, "China's Supercomputing Goal: From 'Zero to Hero'."

Conclusion

In conclusion, the case study of the National Supercomputing Center in Tianjin shows that China's advances in supercomputing hardware have brought accompanying advantages on the application side to at least one industry, oil exploration. This impact is limited, however. While likely allowing oil companies to process data more quickly and cheaply while reducing overhead costs, and perhaps even contributing to a decline in NOC supercomputer ownership, the impact of HPC policy in this area still reflects several weaknesses present in the state of HPC in China as a whole. Oil companies show a strong inclination to purchase hardware and software products from foreign vendors when given the choice, indicating that China's domestic HPC industry has some way to go before it is internationally competitive. Investments have yet to provide substantial assistance to NOCs in the software area. The NSCCs merely represent a new way to run what the companies already had, reflecting the overall gap between hardware and applications persistent in China's HPC environment. And the Tianhe-1A's advertised utilization rate of 70 percent is outpaced by top supercomputers in the United States, which exceed 90 percent at Department of Energy-run labs, showing that inefficiencies exist despite its contributions to the processing needs of NOCs. Thus while its supercomputing venture has succeeded in providing practical economic advantages to national oil companies and doubtlessly had a favorable effect on its energy security calculations, key challenges still exist as China seeks to develop its HPC industry.