



VOLUME 1 (I)

Disclaimer: The research and analysis underlying this report and its conclusions were conducted by the NATO S&T Organization (STO) drawing upon the support of the Alliance's defence S&T community, NATO Allied Command Transformation (ACT), and the NATO Communications and Information Agency (NCIA). This report does not represent the official opinion or position of NATO or individual governments but provides considered advice to NATO and Nations' leadership on significant S&T issues.

FOREWORDS

Now more than ever, geopolitics and strategic decision-making are impacted by, and even driven by, science and technology (S&T). As this trend intensifies, it is vitally important that NATO and Allies understand how decisions made today affect future options, opportunities, and preparedness. To do this, as leaders, we must assess the evolving science and technology environment and Macro Trends against the backdrop of the current era of heightened strategic competition. Taking a 20-year outlook, this report offers an opportunity to better understand these complex relationships. As these trends unfold, it will be increasingly vital that political and military decision-makers not only learn from relevant technical experts but also work closely with trusted partners across society. Ensuring the Alliance benefits from science and technology advancements to the greatest extent possible will also require us to give priority to ethical and legal safeguards, global partnerships, and collaboration both with the private sector and within the scientific community. This whole-of-society approach will enable leaders to assess future risks, opportunities, and choices as they prepare for future scenarios and work to minimise future shocks for the over 1 billion citizens our Alliance defends.

Radmila Shekerinska

NATO Deputy Secretary General

Science and technology is the bedrock of our modern society, ensuring our prosperity and driving our progress. As the body tasked with meeting the collective science and technology needs of the Allies and partners, it is incumbent upon the Science & Technology Organization to provide evidence-based strategic advice for NATO leadership. Given the increasing importance of science and technology for strategic decision-making, it is vital to build on existing



technical knowledge and understand the context in which scientific and technological developments are occurring. The overview of interdependencies between scientific and technical areas and their economic, geopolitical, and social effects and enablers provided by this report offers useful context for understanding our current and future geostrategic environment. The six S&T Macro Trends described in this report therefore empower NATO and Allies' decision-makers to consider the choices before them and how they can best prepare the Alliance today to face future challenges. Continued knowledge-building and investment in science and technology will strengthen NATO's and Allies' ability to outperform the competitors of today and tomorrow and ensure that we remain robust, resilient, and ready to respond to any threat.

Dr Bryan Wells

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INTRODUCTION

This Science & Technology (S&T) Macro Trends Report provides an overview of the socio-technical trends that will shape the technology landscape from 2025 to 2045. It analyses links between emerging and disruptive S&T areas and their macro-economic, geopolitical, and societal effects and enablers.

This Public Release volume represents the latest iteration of the NATO Science & Technology Organization's (STO) flagship research report and builds on the previous version, the S&T Trends Report 2023-2043 published in March 2023. In alignment with previous S&T Trends Reports, this volume aims to build understanding on the impact of S&T on the Alliance's political decision options, defence capabilities, military operations, and enterprise functions.

As a response to the increasing linkages and dependencies between technology and geopolitics, this publication complements existing foresight work across NATO by offering an S&T perspective on trends that will affect diverse aspects of the Alliance over the next 20 years. While targeting a senior leadership audience, this report also aims to be accessible to a wide range of readers, including practitioners from within and outside of the S&T environment.

In offering insights into how S&T shapes geopolitical priorities and vice versa, this report offers a perspective for senior decision-makers on how to respond to challenges on (and over) the horizon by making strategic choices now.



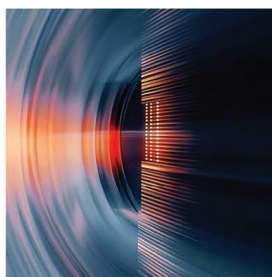


Executive Summary

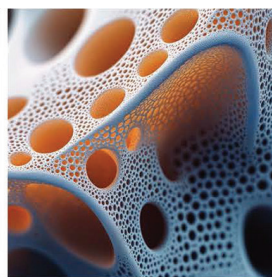
Each of the S&T Macro Trends describes a distinct global trend that is uniquely impacted by and distinctly impacts S&T. These six trends are shaping and/or will shape NATO's strategic landscape and influence how emerging and disruptive technologies (EDTs) continue to evolve. They will also impact how Alliance governments and societies respond to and develop future S&T policy. The following trends are anticipated to define the S&T landscape from 2025-2045, with differing impacts and timelines expected for each.



MACRO TREND 1
Evolving
Competition Areas



MACRO TREND 2
Race for AI and
Quantum Superiority



MACRO TREND 3
Biotechnology
Revolution



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MACRO TREND 1

Evolving Competition Areas

As global strategic competition intensifies, S&T advances will shape and transform the nature of competition, in traditional domains and in non-traditional ones – for example, cyber, space, hybrid and information, and in geographical regions such as the High North. In turn, the continued hybridisation of warfare and heightened importance of multi-domain operations (MDO) are expected to fuel further reliance on S&T across all domains.

Key judgements

- Emerging technologies offer leaders a spectrum of strategic choices to be made now to ensure that the Alliance is fit for the future operating environment.
- Critical technology areas will shape the future of geopolitical competition and, simultaneously, geopolitical competition will fuel future S&T development.
- The continued hybridisation of warfare has not only made shocks from tactics such as economic coercion more likely, but has also heightened the importance of the cyber and space domains in future contests and conflicts.

MACRO TREND 2

Race for AI and Quantum Superiority

Artificial Intelligence (AI) and quantum not only represent technology areas that will transform a diverse range of industries



in the next 20 years, but they are also areas in which competition between dominant actors will accelerate over time. An essential and long-term aspect of this trend will be the challenge of finding, training, and retaining talent.

Key judgements

- Digital transformation (including access to large quantities of quality data, as well as storage and dissemination tools) will remain essential as AI and quantum technology continue to develop.
- Talent acquisition, training, and retention will be a key battleground for technology competition.
- Like-minded nations will need to pool expertise and resources to win this race.

MACRO TREND 3

Biotechnology Revolution

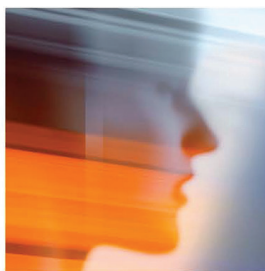
The next revolutionary technology cycle will be driven by synthetic biology. In addition to continuing developments in related technology areas (e.g., biodata and biosensors), this trend will bring issues such as research security (safeguarding sensitive research) and regulation to the forefront.

Key judgements

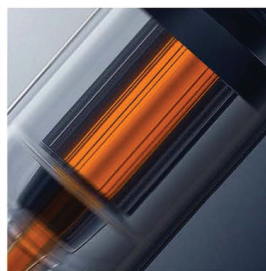
- Synthetic biology and related technologies will have a disruptive, revolutionary impact within the next 20 years, in both the civilian and military realms.
- While the potential benefits from increased biotechnology use are substantial, especially for healthcare, the risks of harmful uses are also enormous. This necessitates careful consideration of security and defence implications, including the protection and sharing of research.
- Research safeguards need to align with our shared values and norms.



MACRO TREND 4
Resource
Divide



MACRO TREND 5
Fragmenting
Public Trust



MACRO TREND 6
Technology Integration
& Dependencies



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MACRO TREND 4

Resource Divide

S&T advancement serves both as a driver of deepening resource divides and as a potential enabler of economic development via AI-enabled solutions, bio- and green technology, and novel/advanced materials. Economic resilience and security as well as NATO's global partnerships will become increasingly crucial in relation to this trend. Techno- nationalism is also expected to be further prioritised by leaders who view technological capability as increasingly integral to economic, societal, and national security needs.

Key judgements

- Climate change will impact the Alliance's shared access to critical resources for S&T innovation.
- Upcoming shocks, especially but not exclusively stemming from climate change, will exacerbate existing tensions between nations that can more easily recover from such shocks and those that cannot.
- Future technology advancement and adoption will act as both a solution to these growing tensions as well as an accelerator of them.

MACRO TREND 5

Fragmenting Public Trust

Trust in science, institutions, and governments is vulnerable to further undermining and fragmentation, and technology acts primarily as an accelerator of these challenges, especially via AI-generated information threats. As a result of these developments, topics such as



strategic communications, digital sovereignty, the need for trustworthy S&T solutions, and improved technology education are expected to increase in importance within the next 20 years.

Key judgements

- Global leadership is needed to encourage the responsible use of EDTs.
- Technology, especially AI, is being used to decrease public trust (in governments, institutions, and science), and the future impact of these developments will be further complicated by rising political polarisation.
- In the long term, tech-fuelled solutions may offer tools for combatting disinformation and misinformation, but in the short term, strategic communications, legal/regulatory mechanisms, and technology education will be increasingly vital.

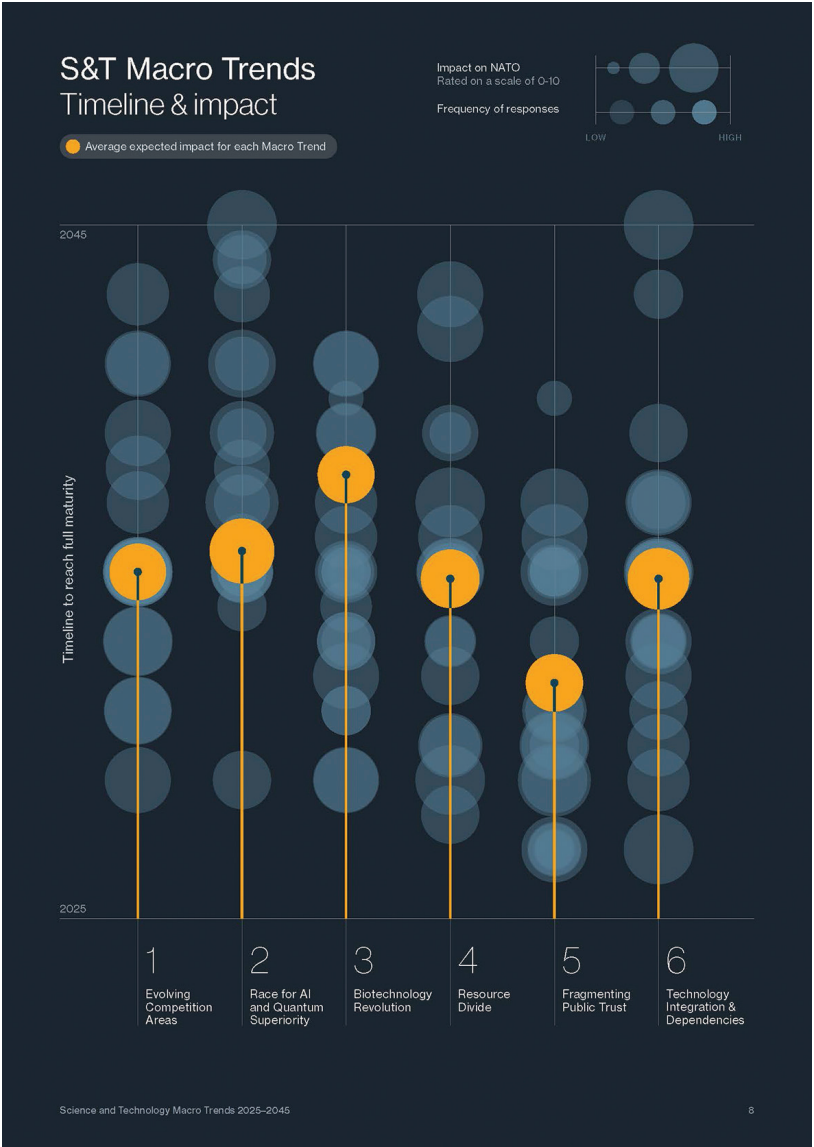
MACRO TREND 6

Technology Integration & Dependencies

While S&T advancements will continue to provide solutions to complex challenges, access to these solutions will be unequal. For those with cutting-edge technology, differences in Concepts of Operations and regulation will pose challenges for interoperability and standards. Meanwhile, as innovation is increasingly driven by the private sector, new challenges for civilian-military integration will emerge, and the long-term effects of increased dependency on S&T across civilian and military domains may bring unexpected consequences.

Key judgements

- Future S&T capabilities need to be interoperable by design.
- Interoperability will become more critical than ever for Allies in the next 20 years, yet new challenges to achieving it will also arise as disparities in technology access, usage, and regulations become more pronounced.
- Economic cooperation is needed with like-minded nations and private sector partners.
- Increasing dependencies on private actors for critical defence needs will become a greater challenge as S&T becomes increasingly essential for a wider range of military operations.





Cross-cutting issues

Within these six S&T Macro Trends, several key themes cut across the S&T and geopolitical areas discussed in the following report. Four primary issues are identified as being particularly significant for all Macro Trends. These are:

- Challenged Rules-based International Order (RBIO)
- Climate change
- Global partnerships
- Increased role of the private sector

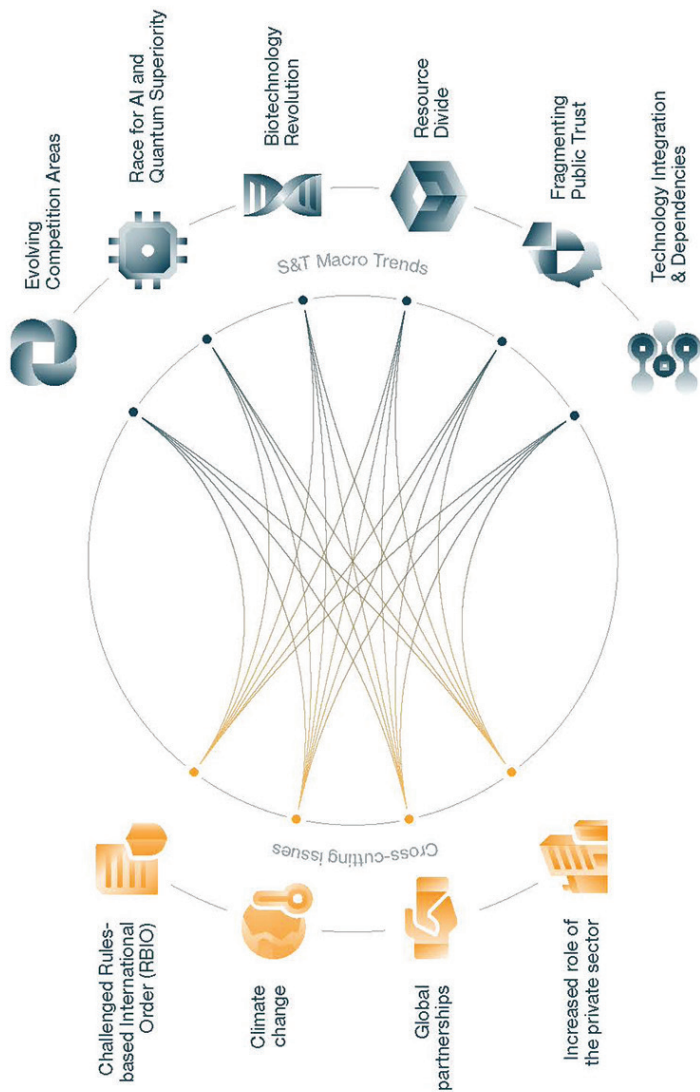
Each represents a driver and/or result of multiple Macro Trends, hence these four issues are simultaneously enabling future S&T advancement and/or will be significantly affected by future S&T development. The cross-cutting issues provide a thematic lens through which to view the S&T Macro Trends and their combined impact, and are therefore highlighted in the trend implications.

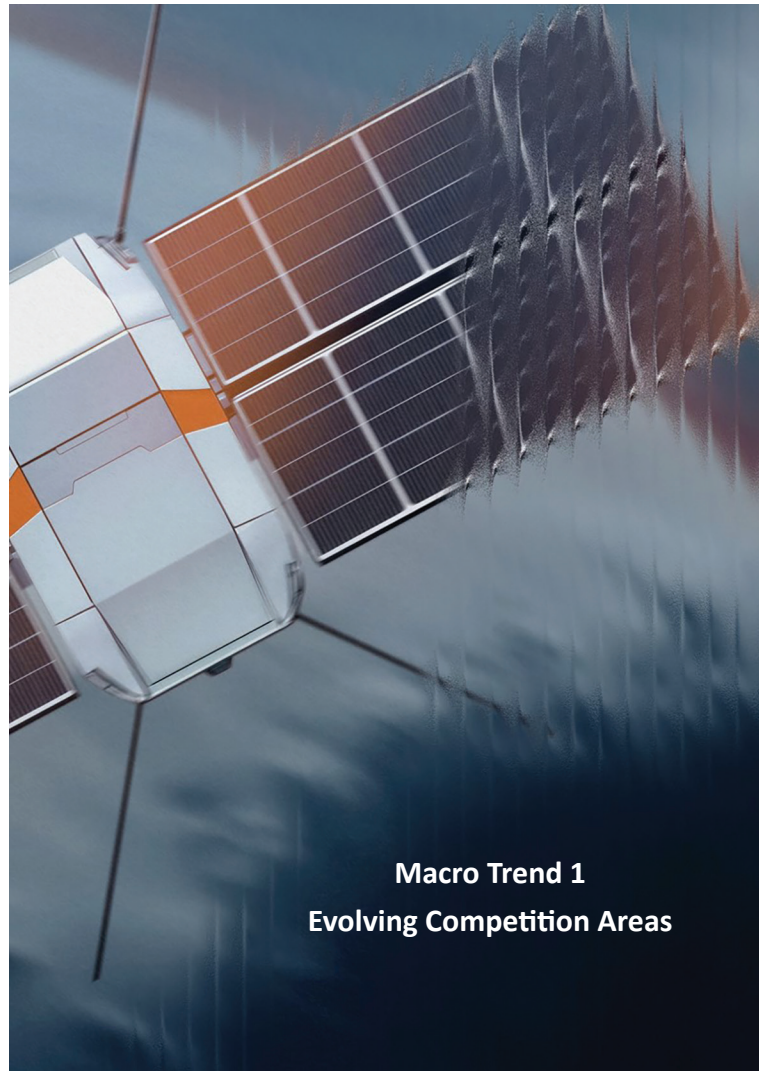
Considerations regarding the promotion of scientific collaboration while simultaneously safeguarding sensitive research or ensuring “research security” is also highly relevant for several Macro Trends. Research security refers to the protection of scientific research – especially that which has defence and security applications – from undesirable foreign state (or non-state) access, influence, or espionage, with the aim of protecting national security and achieving decisive advantage from technology across all instruments of power. These concerns are vital to consider when assessing future S&T development. However, research security was not identified as a primary cross-cutting theme across all six trends.

Report structure

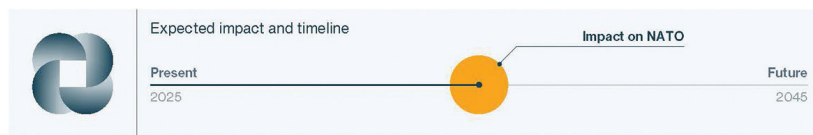
In addition to the key judgements outlined above, this report assesses the six S&T Macro Trends by explaining the background, implications, state of play, and choices for leadership related to each trend.

Cross-cutting issues for the S&T Macro Trends





Macro Trend 1
Evolving Competition Areas



Key judgements

- Emerging technologies offer leaders a spectrum of strategic choices to be made now to ensure that the Alliance is fit for the future operating environment.
- Critical technology areas will shape the future of geopolitical competition and, simultaneously, geopolitical competition will fuel future S&T development.
- The continued hybridisation of warfare has not only made shocks from tactics such as economic coercion more likely, but has also heightened the importance of the cyber and space domains in future contests and conflicts.

1.1 Background

As stated in the NATO Strategic Concept (2022), the current security environment is characterised by “*strategic competition, pervasive instability and recurrent shocks*” (NATO, 2022). In this environment, EDTs are gaining strategic importance and becoming key arenas of global competition. As global competition intensifies, S&T advancements will shape and transform the nature of strategic competition, including in traditional domains and non-traditional ones – for example, hybrid and information warfare or contests in the High North. In turn, the continued hybridisation of warfare (i.e., the combined use of traditional military aggression with tactics such as coercion, influence operations, or sabotage) and heightened importance of multi-domain operations (MDO) will fuel further reliance on S&T across domains, since technology offers vital links between military systems and operations.

Experts widely accept that great power competition is on the rise and shows no sign of abating in the short term (United States Space Force, 2024). While current trends do not necessarily result in the eruption of additional kinetic conflicts, it is especially critical to monitor the full spectrum of friendly-to-confrontational interactions between



great powers and their allies at a time when direct confrontation between powerful (nuclear-armed) nations appears a greater danger than it has been for the past three decades (Lynch, 2020). Viewing this trend through the S&T lens explains how critical technology areas are likely to shape the future of competition as well as how geopolitical competition may fuel future S&T development.

1.2 Implications

Strategic competition is a key driver of S&T development, and at the same time, S&T advancement allows for new areas of competition. This is especially true for the cyber and space domains, where below-threshold attacks are expected to significantly increase in the future. Furthermore, the likelihood of action taken in the cyber or space domain to spur a direct, kinetic conflict is also increasing. Given that everything from the global stock market to GPS relies on space assets, this domain is of particular concern as space becomes more congested and contested.

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Continuous technology advancements have also created opportunities for both state and non-state actors to engage in more diverse forms of conflict – for example, in the cyber domain or through other non-kinetic, hybrid, or grey-zone attacks. Therefore, conflicts in non-traditional domains as well as below-threshold attacks are highly likely to become more commonplace in the next 20 years. Additionally, the fact that innovation, including defence innovation, is primarily driven by the private sector will allow super-empowered individuals to play a role in shaping the future of strategic competition. These developments pose significant challenges for attribution, norm-setting, and crafting proportional responses.

Compounding these challenges, the exponential increase in AI integration could transform standard methods for conflict prevention, leading experts to doubt whether traditional crisis communication mechanisms can sufficiently address coming risks (Lawfare, 2024).

1.3 State of play

Technology has always been central to determining victors in all forms of competition and conflict. However, the current landscape offers more options than ever due to both the existence of additional military domains and evolving applications for technologies in military contexts. Today, advantages from technology are increasingly determinant of battlefield success (NATO, 2022), and these dynamics are generally understood by strategic decision-makers. Taking the United States and the People's Republic of China as examples, the past 2 years alone have demonstrated a notable uptick in US initiatives to prevent China from gaining a technological advantage, as policymakers in both nations clearly consider innovation to be a key factor of economic and military superiority (The Economist, 2024).

Space

The space domain is widely considered to be an increasingly contested environment in which competition for geopolitical and military supremacy is expected to play out, a challenge for which no international consensus exists (United Nations, 2023). While space has long been an enabler of all other military domains, from communications and weather forecasting to tracking adversaries and providing position, navigation, and timing (PNT), its increasing applications have led to greater reliance on its assets over time, making it a critical arena not only for power projection but also operational effectiveness. Space is also characterised by rapid transformation (United States Space Force, 2024) due in large part to increasing access to technology and, as a result, access to space itself.

The increased strategic importance of space and related dependencies for military activities has naturally led to the space domain becoming more militarised over time – for example, through reinvigorated efforts to develop anti-satellite weapons and counter-space capabilities, such as conducting cyber-attacks or jamming/spoofing satellites. In the longer term, accelerated proliferation of earth-to-space (especially anti-satellite) weapons, directed energy weapons, and more sophisticated counter-space capabilities enabled by emerging technologies is not difficult to imagine, especially



*Advantages
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if international norms and regulations for what operations can be conducted in space are not updated to address the risk of a potential space arms race (Center for Arms Control and Non-Proliferation, 2023). These developments are already illustrating the potential for a substantial uptick in space contest and conflict, even if it remains below the threshold of kinetic warfare (Francis et al., 2023).



The exponential increase in space accessibility – via the commercialisation of space and proliferation of civilian usage and, looking further forward, predicted increases in the use of hypersonics and in-space propulsion technologies – will further congest the space environment. Furthermore, as space becomes more congested with commercial and other actors, the potential for miscalculation, mistakes, in-space collisions, and escalating tensions will only heighten in the coming years.

Cyber

The cyber domain is often cited as an equally important arena for near- and medium-term competition (ACT, 2024) as many international actors continue to favour and, due to continued technology advancements, have more options for below- threshold and non-kinetic aggressions. Although shifts in this domain tend to be difficult to track, in part due to attribution challenges, it is clear that the importance and impact of cyber conflict should not be underestimated. Even in scenarios that are largely defined as conventional warfare, cyber plays a crucial role for all sides. For example, the Russian Federation conducted a cyber-attack against Ukraine prior to its full-scale land invasion of Ukrainian territory in 2022, with the aim of disrupting command and control (C2) capabilities at a critical moment for the Ukrainian military (U.S. Department of State, 2022). Increasingly sophisticated cyber technologies will continue to fuel the hybridisation of warfare, which is likely to create more frequent disruptions caused by more precise targeting of critical and civilian infrastructure and financial systems.

The hybridisation of warfare

The continued hybridisation of warfare extends beyond traditional military domains, and technological advancements are shaping these developments as well. For example, the combined use of AI with robotics and autonomous systems already enables militaries to choose from more diverse types of operations and effects, especially below-threshold activities. Advanced technologies not only enable more and more precise attacks, but also are increasingly difficult to detect and attribute (Mills, 2023). The challenges and opportunities posed by these developments are likely to increase in importance not only as a result of global competition, but also at the operational level, as MDO are more widely deployed. Military experts anticipate an increase in MDO in the near and medium term, due to a growing need for militaries to synchronise efforts and achieve real-time integration across numerous domains simultaneously (ACT, 2023).

Technological developments are also increasing opportunities for hybrid warfare tactics such as economic coercion and the spread of information threats (more on the latter in Macro Trend 5). Regarding



Technological developments are also increasing opportunities for hybrid warfare tactics.



economic coercion, it is recognised that technology is a major factor regarding nations using export controls to exert influence, as seen for example with recent US policy shifts on semiconductors (The Economist, 2023). More broadly, recent national, international, and intragovernmental initiatives (Höra, Weiss, 2024; Chatham House, 2023), focused on economic security and supply chain resilience have been fuelled by several factors, including increased great power competition, Russia’s war of aggression against Ukraine, and the COVID-19 pandemic. However, these efforts also stem from the increased importance of technology and critical dependencies that offer opportunities for coercion, influence, and exploitation. As competition increases, there has also been an uptick in the weaponisation of economic dependencies or “*weaponised interdependence*” (European Journal of International Law, 2023).

Economic security will therefore require more than de-risking supply chains or safeguarding critical infrastructure. Consistent commitment to prioritise technology development and fostering innovation and investment is also necessary. Additionally, responses

to these challenges must involve cooperation among diverse international actors to align economic security priorities with shared strategic objectives (Searight, 2024; Heard, 2020).

Regional partnerships

Regional divides act as both an enabler of global competition and a result of it. Experts predict that, in addition to more frequent global shocks, growing strategic competition may also encourage further regionalisation. In addition to economic and technology-related factors such as the aim to decrease dependencies or de-risk, this trend will likely also be affected by climate change, migration, demographic changes, and rising authoritarianism. Smaller nations in particular are likely to be affected as more frequent economic, climate, security, and geopolitical disruptions will heighten the importance of having reliable and stable trade regimes.

Therefore, smaller economic actors may be forced to rely on partners who not only offer the cheapest solutions but those who appear to be most resilient against coming shocks. One possible result could be that the influence of economic blocs such as BRICS (originally composed of Brazil, Russia, India, China, and South Africa, but has since expanded its membership) will grow. Developments like this would challenge the influence of institutions such as the International Monetary Fund and World Bank and likely contribute to further instability (Hill et al., 2020).

Growing discontent in the southern hemisphere or “Global South”, including parts of Africa and the Middle East, Central and East Asia, and Latin America, is also likely to impact global competition. Many nations in these regions hope to rebalance global power dynamics and encourage more equitable divisions of prosperity, security, and technology. These aims are made significantly more difficult by climate change, which disproportionately affects these same areas (Hogan, Patrick, 2024). Simultaneously, these are also the nations in which competition for global influence will likely intensify most as traditional global powers attempt to deepen existing ties or build new alliances (Parameswaran, 2024). In this context, the importance of existing international partnerships would increase exponentially.



The fundamental dependence of civilians and militaries on space assets represents a crucial vulnerability that is only increasing over time.

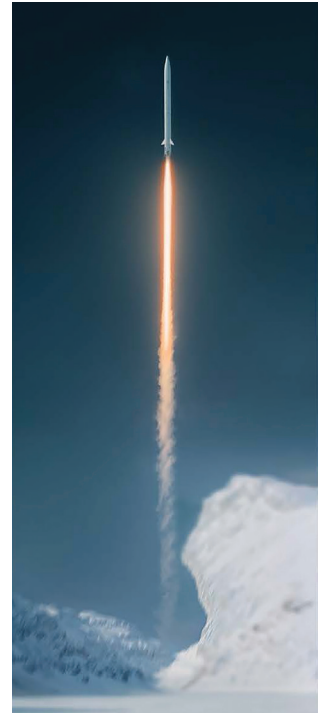


However, these relationships could also become less predictable if new alliances are potentially determined by ideological and political values or short-term economic security and technology needs rather than long-standing trade agreements or geography (Government of Canada, 2024).

1.4 Choices for leadership

As global strategic competition intensifies, unpredictability and uncertainty are also on the rise, making it difficult to anticipate which shocks to prepare for and when. Decision-makers will benefit from considering multiple future scenarios, possibly using advanced immersive simulation and modelling opportunities to better understand the choices available. However, no matter the future contest or conflict scenario, it is clear that traditional notions of deterrence and escalation must adapt to the increasingly technology-dependent defence environment.

Leadership will also need to address the growing importance of space. Although all military domains rely on technology, the fundamental dependence of civilians and militaries on space assets represents a crucial vulnerability that is only increasing over time. In the civilian realm alone, space-based systems are integral to more than 50% of critical infrastructure and services in members of the Organisation for Economic Co-operation and Development (OECD) (OECD, f.a.). As the importance of space resources and technologies grows, leaders should consider options for building resilience and responding to future tensions (Ziegler et al, 2024). Looking forward, serious efforts must also be dedicated to investigating how international legal frameworks can be leveraged to mitigate the growing risk of space conflict (University of Exeter, 2024).



(To be continued)

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