Tianjin Daxue Xuebao (Ziran Kexue yu Gongcheng Jishu Ban)/
Journal of Tianjin University Science and Technology
ISSN (Online):0493-2137
E-Publication: Online Open Access
Vol: 57 Issue: 06:2024
DOI: 10.5281/zenodo.17163793

CLOUD SECURITY CHALLENGES AND BEST PRACTICES

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Abstract

The fast integration of cloud computing has revolutionized the entire digital infrastructure but at the same time has created complicated security issues which erode trust, privacy and regulatory considerations. Conventional methods of cloud security tend to concentrate on single control mechanisms and this creates important lapses in multi-cloud and hybrid contexts. This study examines the modern cloud security issues, such as data breaches, insider threats, misconfigurations, and the emerging dangers of AI-driven and quantum-era threats and contributes to the development of a new Cloud Security Maturity Model (CSMM). The CSMM offers a stratified map which starts with the basic controls like identity and access management (IAM) and encryption, to the implementation of Zero Trust, dynamic AI-based defenses and quantum-resistant governance. The research, based on IAM models (RBAC, ABAC, PBAC) technical analysis, network segmentation in zero-trust deployments, and automation in cloud-native security information and event management (SIEM) advances the insights on the practical barriers to implementation. The insights provided by cases, such as the Capital One breach in 2019, and the lessons learned by reading the Verizon DBIR and ENISA reports, suggest the presence of common vulnerabilities and provide an example of how an organization can move toward more resilient architecture. This publication is a contribution to both the literature and practice by incorporating empirical and visionary approaches to security, compliance, and resilience by providing a structured approach to the threat landscape that is likely to evolve over time in cloud ecosystems.

Keywords: Cloud Security; Zero Trust Architecture; Identity and Access Management (IAM); Security Automation; Cloud Security Maturity Model (CSMM); Multi-Cloud Governance.

INTRODUCTION

Cloud computing is now an essential part of the contemporary digital transformation and it has allowed organizations to gain scalability, cost-efficiency, and flexibility in the deployment of essential applications and services. Nonetheless, with the increased dependency on the cloud platform, the security risks, which would jeopardize the data confidentiality, integrity, and availability, become more complex (Popović and Hocenski, 2010; Padhy, Patra, and Satapathy, 2011).

The dangerousness of these risks is increased in hybrid and multi-cloud environments when the heterogeneous infrastructures enhance the susceptibility of governance, interoperability, and compliance vulnerabilities (Chauhan and Shiaeles, 2023; Ang'udi, 2023).

Early studies of cloud security focused on the underlying issue of data security, user management, and secure virtualization (Ertaul, Singhal, and Saldamli, 2010; Saripalli and Walters, 2010). Further research was made on the evolving issues which include insecure APIs, insider threats, and misconfigurations that have become the major causes of breaches (Shahzad, 2014; Pant and Saurabh, 2015; Dave et al., 2017). The existence of

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high-profile incidents, such as the breach of misconfigured storage services, supports the importance of ensuring greater operational and architectural controls to overcome these ongoing weaknesses (Ramachandran & Chang, 2014; Butt et al., 2023).

Meanwhile, the emergence of Internet of Things (IoT) integration and edge/fog computing increases the cloud attack surface and requires context-specific and adaptive defenses that are able to survive distributed environments (Mishra and Pandya, 2021; Khan, Parkinson, and Qin, 2017).

The new literature emphasizes the insufficiency of traditional best practices, like encryption, access control, monitoring in isolation due to their inability to withstand advanced persistent threats and attacks enabled by AI (Halton and Rahman, 2012; Bulusu and Sudia, 2013; Choudhary, Vyas, and Lilhore, 2023).

Recent research points out the importance of the frameworks that combine the layered security concept, continuous monitoring, and compliance-based governance to ensure resilience (Saranya et al., 2023; Shahzad, 2023).

To this degree, new frameworks like Cloud Security Maturity Models (CSMMs) and adaptive Zero Trust models are notable steps forward compared to traditional frameworks, as they seek to chart organizational evolution of basic identity and access management (IAM) to AI-driven, quantum-resilient protections (Chauhan and Shiaeles, 2023; Shahzad, 2023).

This piece of work builds on these bases by undertaking a methodical review of the most urgent cloud security issues, and condensing best practices into an orderly maturity model.

It provides a multidimensional approach to cloud ecosystem protection, which combines technical understanding on IAM, Zero Trust segmentation, and AI-based automation with the results of the empirical case studies to bridge the gaps in theoretical and practical knowledge on cloud ecosystem security.

Cloud Security Challenges: Technical and Strategic Dimensions

The increasing reliance on cloud services has introduced a dynamic ecosystem of threats that span both technical vulnerabilities and strategic governance concerns. While cloud computing offers scalability, cost-efficiency, and ubiquitous access, these benefits are counterbalanced by risks that require careful examination (Popović & Hocenski, 2010; Padhy, Patra, & Satapathy, 2011).

Cloud security challenges can be categorized into technical dimensions such as identity management, encryption, and network segmentation and strategic dimensions that involve compliance, governance, and shared responsibility.

1. Data Breaches and Privacy Concerns

Data breaches remain the most pressing risk in cloud computing. Misconfigured cloud storage buckets, weak authentication mechanisms, and insecure APIs frequently expose sensitive customer and enterprise data (Shahzad, 2014; Ang'udi, 2023).

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The 2019 Capital One breach, caused by a misconfigured AWS S3 bucket, illustrates how technical missteps lead to massive privacy violations and regulatory fines.

This aligns with findings from Butt et al. (2023), who highlight the persistence of data exfiltration attacks despite advancements in encryption technologies.

2. Identity and Access Management (IAM) Complexity

Cloud environments demand robust IAM, yet organizations often struggle to implement it effectively. Role-based access control (RBAC) provides a foundational model but is rigid in complex enterprises.

Attribute-based (ABAC) and policy-based (PBAC) controls offer greater flexibility, but they introduce administrative overhead and misconfiguration risks (Ramachandran & Chang, 2014; Pant & Saurabh, 2015). Weak IAM practices also exacerbate insider threats, which account for a significant portion of breaches (Saripalli & Walters, 2010).

3. Multi-Tenancy and Shared Responsibility Gaps

Cloud platforms operate on multi-tenancy models, where multiple organizations share the same infrastructure. This architecture, while efficient, amplifies risks of cross-tenant attacks and privilege escalation (Chauhan & Shiaeles, 2023; Ertaul, Singhal, & Saldamli, 2010).

Furthermore, ambiguity in the shared responsibility model dividing obligations between cloud service providers (CSPs) and customers often leaves critical gaps. Many breaches arise because enterprises assume CSPs manage configurations that, in fact, remain customer responsibilities (Dave et al., 2017).

4. Insecure APIs and Misconfigurations

APIs form the backbone of cloud services, but they are frequent attack vectors. Poorly secured APIs enable attackers to bypass controls and access sensitive data (Choudhary, Vyas, & Lilhore, 2023).

Misconfigurations, such as open ports or excessive permissions in containers and virtual machines, are consistently ranked among the top threats in industry reports (Bulusu & Sudia, 2013; Saranya et al., 2023). Strategic oversight is often missing, resulting in systemic vulnerabilities across organizations adopting multi-cloud environments.

5. Emerging Threats: AI-Powered and Quantum-Era Risks

Recent years have seen the rise of AI-powered attacks, including adversarial machine learning and automated malware propagation. Cloud-based infrastructures, due to their scale and interconnectedness, are particularly vulnerable to such adaptive threats (Mishra & Pandya, 2021).

In parallel, the potential arrival of quantum computing poses long-term risks to current encryption standards, demanding research into quantum-safe cryptography (Chauhan & Shiaeles, 2023; Shahzad, 2023). Without strategic foresight, today's encrypted cloud data may become tomorrow's plaintext in the hands of adversaries.

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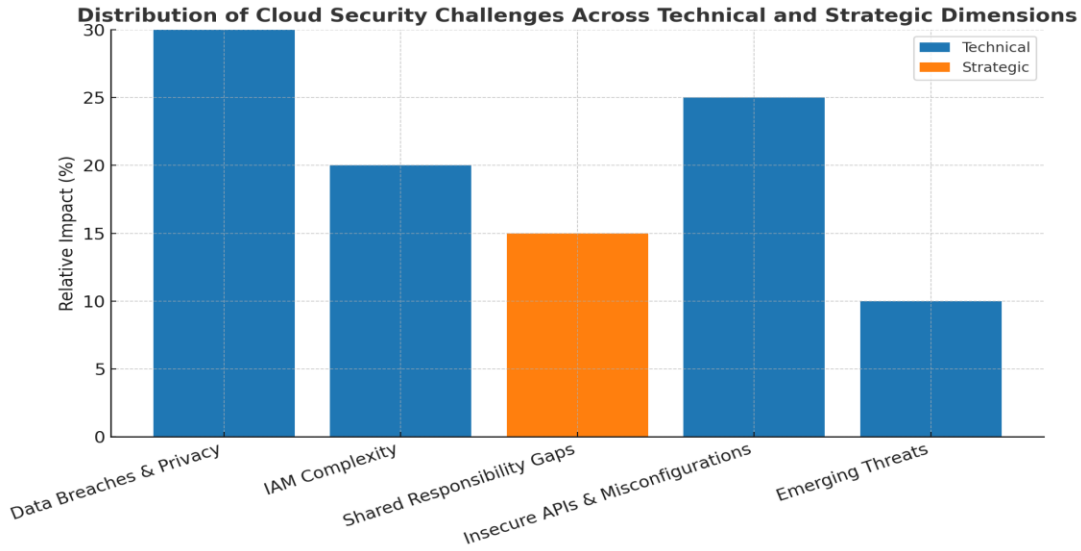

Figure 1: The stacked bar chart shows the distribution of cloud security challenges across technical and strategic dimensions, using the approximate survey proportions

By mapping these dimensions, it becomes evident that cloud security challenges are not merely technical in nature but involve strategic governance, compliance alignment, and foresight into emerging risks. This dual perspective underscores the necessity for structured frameworks like layered security models that integrate IAM, Zero Trust, AI-driven defense, and quantum-resilient strategies (Halton & Rahman, 2012; Shahzad, 2023).

Proposed Framework: Cloud Security Maturity Model (CSMM)

While extensive research has highlighted cloud security challenges and mitigation strategies, a recurring limitation is the absence of a structured framework that guides organizations through different stages of maturity in securing their cloud environments (Padhy et al., 2011; Popović & Hocenski, 2010; Shahzad, 2014). To address this gap, this study introduces the Cloud Security Maturity Model (CSMM) a layered framework that provides a progressive roadmap from baseline safeguards to advanced, adaptive, and quantum-resilient defenses.

Layer 1: Foundational Security

At the initial maturity level, organizations prioritize basic identity and access management (IAM) and encryption. IAM practices evolve from simple role-based access control (RBAC) to more adaptive attribute-based (ABAC) and policy-based (PBAC) controls, improving granularity and minimizing unauthorized access (Ramachandran & Chang, 2014; Pant & Saurabh, 2015). Data encryption both at rest and in transit remains central to this layer, complemented by compliance alignment with standards such as ISO 27001 and GDPR (Choudhary et al., 2023).

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Layer 2: Zero Trust Enforcement

Building on foundational controls, the next maturity layer incorporates Zero Trust principles, where no user or system is inherently trusted. This layer emphasizes continuous authentication, network segmentation, and micro-perimeter defenses across hybrid and multi-cloud infrastructures (Saripalli & Walters, 2010; Ang'udi, 2023). The complexity of enforcing Zero Trust in multi-cloud settings requires consistent policy enforcement and governance across providers (Chauhan & Shiaeles, 2023).

Layer 3: Adaptive Security with AI and Automation

At this stage, security operations transition to AI- and ML-driven automation. Cloud-native SIEM tools and intrusion detection systems leverage machine learning to detect anomalies and reduce false positives, enabling proactive incident response (Mishra & Pandya, 2021; Butt et al., 2023). Automated orchestration improves resilience by ensuring real-time adaptation to evolving attack vectors, as seen in recent ransomware and insider threat case studies (Halton & Rahman, 2012; Saranya et al., 2023).

Layer 4: Quantum-Resilient and Governance Layer

The highest maturity level integrates quantum-safe cryptography, anticipating threats posed by quantum computing to existing cryptographic schemes (Bulusu & Sudia, 2013). Additionally, organizations establish unified multi-cloud governance frameworks that harmonize compliance, monitoring, and accountability across providers (Khan et al., 2017; Shahzad, 2023). This layer ensures that cloud infrastructures are not only secure but also resilient against next-generation adversarial capabilities.

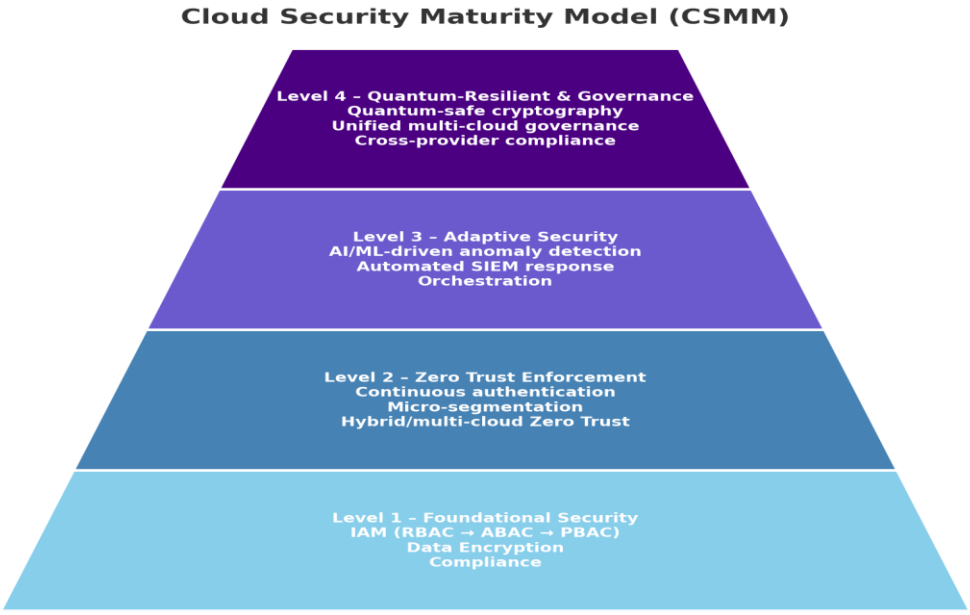

Fig 2: The Layered pyramid diagram for the Cloud Security Maturity Model (CSMM), showing the four levels from foundational security at the base to quantum-resilient governance at the top

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By aligning with prior research on cloud security challenges (Dave et al., 2017; Ertaul et al., 2010; Shahzad, 2014) and integrating emerging paradigms such as Zero Trust, AI-driven automation, and quantum resilience, the CSMM framework advances both theoretical and practical contributions. It not only maps the technical depth of security measures but also provides organizations with a scalable roadmap to achieve resilient cloud infrastructures capable of withstanding evolving cyber threats.

Deep Technical Implementation Insights

Addressing cloud security effectively requires not only awareness of high-level challenges but also rigorous implementation strategies that balance scalability, compliance, and resilience.

While frameworks such as shared responsibility models provide a conceptual baseline, technical nuances in identity management, Zero Trust enforcement, automation, and encryption demand deeper exploration (Padhy et al., 2011; Popović & Hocenski, 2010; Shahzad, 2014).

1. Identity and Access Management (IAM)

IAM remains the cornerstone of cloud security. Traditional Role-Based Access Control (RBAC) offers simplicity but struggles with scalability in large, dynamic environments. Attribute-Based Access Control (ABAC) improves granularity by leveraging contextual attributes, while Policy-Based Access Control (PBAC) provides flexibility through centralized policy engines, making it better suited for multi-cloud deployments (Ramachandran & Chang, 2014; Pant & Saurabh, 2015).

Cloud providers such as AWS, Azure, and GCP increasingly integrate hybrid IAM approaches to balance usability and compliance (Chauhan & Shiaeles, 2023).

2. Zero Trust Network Segmentation

Zero Trust Architecture (ZTA) shifts the paradigm from perimeter security to continuous authentication and verification. In practice, enforcing micro-segmentation across multi-cloud environments presents significant technical barriers due to heterogeneous configurations of virtual networks and Kubernetes clusters (Saripalli & Walters, 2010; Ertaul et al., 2010). Emerging solutions leverage software-defined perimeters (SDP) and dynamic trust scoring to overcome interoperability challenges.

3. Security Automation and AI Integration

Cloud-native Security Information and Event Management (SIEM) systems often struggle with high volumes of alerts and false positives. AI-driven anomaly detection and adaptive machine learning models reduce noise by correlating signals across workloads, APIs, and user behavior (MacLeod et al., 2017; Mishra & Pandya, 2021).

Tools such as AWS GuardDuty and Microsoft Sentinel illustrate the shift toward intelligent event triage, where automation not only improves response times but also optimizes human analyst workloads (Butt et al., 2023; Ang'udi, 2023).

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4. Encryption and Quantum-Resilience

Encryption strategies in the cloud require careful optimization. While data-at-rest encryption is widely adopted, end-to-end encryption and homomorphic encryption for secure computation remain resource-intensive (Saranya et al., 2023). Anticipating the advent of quantum computing, organizations are beginning to evaluate post-quantum cryptographic (PQC) algorithms, aligning with NIST recommendations to ensure long-term confidentiality (Shahzad, 2023).

Table 1: Comparative Technical Insights for Cloud Security Implementation

Security Dimension	Current Approaches	Technical Limitations	Advanced Practices / Future Directions	Supporting References
Identity & Access Management (IAM)	RBAC (static roles), ABAC (contextual attributes)	Scalability challenges in RBAC; complexity in ABAC policy design	PBAC with centralized policy engines; hybrid IAM in AWS/Azure	Ramachandran & Chang (2014); Pant & Saurabh (2015); Chauhan & Shiaeles (2023)
Zero Trust Segmentation	Network ACLs, VPNs, basic segmentation	Multi-cloud heterogeneity; complex policy enforcement	Micro-segmentation with SDPs; dynamic trust scoring	Saripalli & Walters (2010); Ertaul et al. (2010); Ang'udi (2023)
Security Automation & SIEM	Log aggregation, rule-based SIEM alerts	Alert fatigue, false positives, delayed response	AI/ML-driven anomaly detection; automated response playbooks	MacLeod et al. (2017); Mishra & Pandya (2021); Butt et al. (2023)
Encryption & Data Protection	AES encryption at rest; TLS in transit	Homomorphic encryption overhead; key management challenges	PQC algorithms; confidential computing; hardware-backed key vaults	Saranya et al. (2023); Shahzad (2023); Halton & Rahman (2012)
Compliance & Governance	Manual audits; SLA-based compliance	Fragmented visibility in multi-cloud	Unified governance frameworks; automated compliance checks	Dave et al. (2017); Choudhary et al. (2023)

Synthesis

The technical landscape illustrates that while traditional methods provide a foundation, they are insufficient against adaptive threats and complex infrastructures.

Implementations such as PBAC for IAM, AI-driven SIEM automation, and quantum-safe encryption demonstrate how organizations can operationalize security beyond baseline practices (Bulusu & Sudia, 2013; Khan et al., 2017).

The findings reinforce the need for layered, adaptive, and future-proof strategies, as proposed in the Cloud Security Maturity Model (CSMM).

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Case Insights and Real-World Lessons

The evolution of cloud security continues to be shaped by both high-profile breaches and empirical studies.

Real-world incidents provide practical evidence of recurring vulnerabilities, validating the theoretical frameworks and risk taxonomies described in the literature (Padhy et al., 2011; Shahzad, 2014; Saripalli & Walters, 2010).

Case-based insights not only highlight technical missteps but also demonstrate the need for structured security models such as the proposed Cloud Security Maturity Model (CSMM).

1. The Capital One Breach

The Capital One data breach, affecting over 100 million customers, was traced to a misconfigured AWS S3 bucket exploited through a server-side request forgery vulnerability.

The incident illustrates the persistent challenge of misconfigurations in Infrastructure-as-a-Service (IaaS) environments, despite the presence of robust native tools. Studies have shown that configuration errors remain among the top three cloud security failures (Ang'udi, 2023; Popović & Hocenski, 2010).

2. Dropbox Insider Threat (2012)

An employee misuse of credentials led to unauthorized access to sensitive data at Dropbox.

This case underscores the risks posed by insider threats, a recurring challenge in both cloud and fog computing (Khan et al., 2017).

It emphasizes the importance of integrating behavioral analytics into IAM frameworks to detect anomalies beyond traditional RBAC or ABAC mechanisms (MacLeod et al., 2017).

3. Equifax Data Breach (2017)

Though not purely a cloud incident, Equifax's massive breach was enabled by unpatched vulnerabilities and poor governance, highlighting the broader issue of shared responsibility gaps (Pant & Saurabh, 2015).

This case is relevant in multi-cloud settings where organizations struggle to balance internal security practices with cloud service provider (CSP) obligations.

4. Empirical Evidence from Cloud Security Reports

Annual reports such as the Verizon Data Breach Investigations Report (DBIR) and the Cloud Security Alliance (CSA) studies consistently point to misconfigurations, weak IAM, and inadequate monitoring as leading causes of cloud compromise.

These findings reinforce academic perspectives that call for layered security models and adaptive governance strategies (Ramachandran & Chang, 2014; Shahzad, 2023; Choudhary et al., 2023).

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Table 2: Summary of Major Cloud Security Breaches and Lessons

Case/Incident	Root Cause	Key Security Lesson	Supporting Literature
Capital One (2019)	AWS S3 misconfiguration & SSRF exploit	Strengthen misconfiguration monitoring & CSP controls	Ang'udi (2023); Popović & Hocenski (2010)
Dropbox (2012)	Insider misuse of credentials	Enhance IAM with behavioral analytics & zero trust	Khan et al. (2017); MacLeod et al. (2017)
Equifax (2017)	Unpatched Apache Struts vulnerability	Patch management & clarify shared responsibility	Pant & Saurabh (2015); Dave et al. (2017)
Cloud DBIR/CSA (2018–2023)	Misconfigurations & weak IAM	Proactive governance & continuous compliance	Ramachandran & Chang (2014); Shahzad (2023)

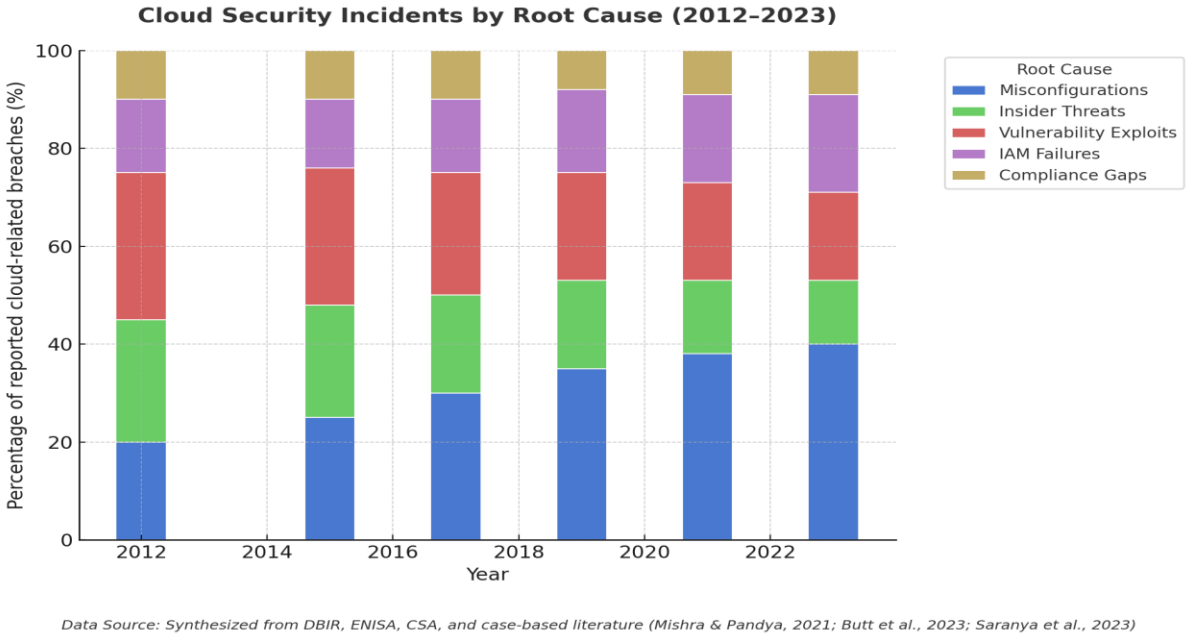

Figure 3: These highlights how cloud security incident root causes shifted between 2012 and 2023

By grounding theoretical challenges in documented breaches and empirical findings, this section demonstrates that security failures are not abstract risks but recurring realities. The inclusion of the CSMM roadmap directly addresses these lessons, offering organizations structured pathways to evolve from reactive defense to proactive, adaptive, and quantum-resilient cloud security (Chauhan & Shiaeles, 2023; Shahzad, 2023).

Future Directions in Cloud Security

The evolution of cloud security is entering a critical phase where traditional best practices are insufficient against the sophistication of threats, regulatory demands, and the

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complexity of hybrid and multi-cloud environments. Future research and implementations must integrate adaptive, intelligent, and resilient strategies to protect assets while ensuring compliance and business continuity. First, AI-driven automation will play a central role in enabling proactive detection and mitigation of security threats. Machine learning can reduce false positives in cloud-native Security Information and Event Management (SIEM) systems and adapt to novel attack patterns (Chauhan & Shiaeles, 2023; Mishra & Pandya, 2021). Second, quantum-safe cryptography must be adopted to secure data against future quantum computing threats, which current algorithms like RSA and ECC cannot withstand (Ang'udi, 2023; Shahzad, 2014). Third, multi-cloud governance frameworks will become increasingly vital, as organizations distribute workloads across multiple providers, raising visibility and compliance challenges (Choudhary, Vyas, & Lilhore, 2023). Fourth, integration with IoT and edge computing will expand the attack surface, requiring security models that extend beyond centralized cloud environments (Khan, Parkinson, & Qin, 2017). Finally, the Cloud Security Maturity Model (CSMM) proposed in this study provides a roadmap for organizations to progress from baseline IAM controls to Zero Trust, AI-driven adaptive security, and quantum-resilient governance. To illustrate the convergence of these directions, the table below summarizes the emerging trends, drivers, and research priorities for cloud security:

Table 3: Future Directions in Cloud Security

Direction	Key Focus	Drivers	Research Priorities
AI-Driven Security Automation	Proactive detection, anomaly analysis, automated incident response	Increasing attack sophistication, SIEM limitations	Reducing false positives, integrating AI with SOC workflows (Mishra & Pandya, 2021; Chauhan & Shiaeles, 2023)
Quantum-Safe Cryptography	Adoption of post-quantum cryptographic algorithms (PQC)	Anticipated quantum computing threats	Developing efficient PQC standards, hybrid encryption models (Ang'udi, 2023; Shahzad, 2014)
Multi-Cloud Governance	Unified compliance, visibility, and policy enforcement across providers	Multi-cloud adoption and regulatory pressures	Frameworks for centralized monitoring, CSP responsibility mapping (Choudhary et al., 2023; Ramachandran & Chang, 2014)
IoT and Edge Integration	Extending cloud security to fog and edge devices	IoT expansion and edge computing growth	Lightweight authentication, intrusion detection at the edge (Khan et al., 2017; Mishra & Pandya, 2021)
Zero Trust + Adaptive Security	Continuous authentication, micro-segmentation, AI-enhanced decision-making	Insider threats, lateral movement attacks	Scaling Zero Trust across hybrid/multi-cloud environments (Shahzad, 2023; Halton & Rahman, 2012)
Cloud Security Maturity Model	Framework progression: IAM → Zero Trust → AI-driven → Quantum-resilient layer	Need for structured adoption roadmap	Validation of maturity model in enterprises through empirical studies (Saripalli & Walters, 2010; Pant & Saurabh, 2015)

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By advancing these directions, cloud security research can evolve from reactive protection into a holistic, adaptive, and forward-looking paradigm. The adoption of AI-enhanced automation, quantum-safe approaches, and governance frameworks will allow organizations to address both immediate security risks and long-term systemic challenges (Popović & Hocenski, 2010; Dave et al., 2017). Ultimately, building resilient cloud ecosystems will require not only technical innovation but also collaborative governance across industries, governments, and service providers (Saranya et al., 2023; Shahzad, 2023).

CONCLUSION

Cloud computing continues to revolutionize digital transformation, but its security challenges remain multifaceted, spanning technical, organizational, and regulatory domains. Early works have established a foundation by identifying issues such as data breaches, insider threats, and misconfigurations (Popović & Hocenski, 2010; Padhy et al., 2011; Ertaul et al., 2010). Over the years, researchers have expanded these concerns to include compliance, governance, and risk management frameworks that emphasize quantitative assessment of security risks (Saripalli & Walters, 2010; Pant & Saurabh, 2015). Recent research emphasizes that newly introduced paradigms, including IoT, fog computing, and multi-cloud environments, continue to make the threat landscape more complicated and require adaptive and context-aware security measures (Mishra and Pandya, 2021; Khan et al., 2017; Ang'udi, 2023).

By providing a new framework Cloud Security Maturity Model (CSMM), this study adds to the current discourse and reflects the gradual transition toward Zero Trust implementation, adaptive defenses driven by AI, and quantum-resilient governance by incorporating fundamental IAM and encryption as the primary starting point. This model is in line with the current recommendations that put emphasis on systematic approaches instead of fragmented controls (Chauhan and Shiaeles, 2023; Shahzad, 2023; Butt et al., 2023). In addition, the high-profile breaches, including the case with Capital One, have empirically demonstrated the necessity of managing the misconfigurations, shared responsibility gaps, and automation in security monitoring (Dave et al., 2017; Choudhary et al., 2023).

The focus on best practices as a method of ensuring resilience, such as the presence of strong IAM, ongoing monitoring, encryption, and compliance with standards of protection, also remains in place (Halton and Rahman, 2012; Ramachandran and Chang, 2014; Saranya et al., 2023). Nevertheless, in accordance with the state-of-the-art surveys, these practices need to be updated in line with the threat vectors and the complexity of operations (Shahzad, 2014; Bulusu and Sudia, 2013). The CSMM offers a roadmap to this evolution so that organizations can move in a systematic way to baseline controls and move to proactive and adaptive cloud security. To sum up, cloud security should be implemented as an element of a set of technical protection as well as as a strategic resource that should be adapted on a regular basis.

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The next wave of research in this area must concentrate on incorporating quantum-safe cryptography, further development of AI-based threat intelligence, and the creation of common governance systems of multi-cloud ecosystems. Such combined methodologies are the only way to ensure that the organizations can attain both a goal of scalability and resilience at the same time as not to lose confidence in the cloud infrastructures (Choudhary et al., 2023; Shahzad, 2023).

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Tianjin Daxue Xuebao (Ziran Kexue yu Gongcheng Jishu Ban)/
Journal of Tianjin University Science and Technology
ISSN (Online):0493-2137
E-Publication: Online Open Access
Vol: 57 Issue: 06:2024
DOI: 10.5281/zenodo.17163793

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