

Cloud Security Best Practices Derived from Mission Thread Analysis

Timothy Morrow
Vincent LaPiana
Don Faatz
Angel Hueca

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Abstract

This report presents four important security practices that are practical and effective for improving the cybersecurity posture of cloud-deployed information technology (IT) systems. These practices help to address the risks, threats, and vulnerabilities that organizations face in deploying or moving applications and systems to a cloud service provider (CSP).

The practices address cloud security issues that consumers are experiencing, illustrated by several recent cloud security incidents. The report demonstrates the practices through examples using cloud services available from Amazon Web Service (AWS), Microsoft, and Google.

The presented practices are geared toward small and medium-sized organizations; however, all organizations, independent of size, can use these practices to improve the security of their cloud usage. The focus here is on hybrid deployments where some IT applications deploy or move to a CSP while other IT applications remain in the organization's data center. Small and medium-sized organizations likely have limited resources; where possible, these practices describe implementation approaches that may be effective in limited-resource situations.

1 Introduction

This report presents a collection of security practices that are practical and effective for improving the cybersecurity posture of cloud-deployed IT systems. We developed these practices by identifying the risks, threats, and vulnerabilities faced in deploying or moving applications and systems to a cloud service provider (CSP) [Morrow 2019]. We defined five mission threads¹ and used them to study the effect of these risks, threats, and vulnerabilities on cloud-based application and system security.² Analysis of these mission threads identified a collection of four practices organizations should follow to manage cybersecurity risk when deploying applications and systems to the cloud.

The four practices presented here are not the complete collection of actions needed to securely use cloud computing. These four practices address the specific risks created by the specific threats analyzed in the mission threads. These four practices should be complemented with practices provided by CSPs, general cybersecurity practices, regulatory compliance requirements, and practices defined by cloud trade associations, such as the Cloud Security Alliance [CSA 2018].

These practices are geared toward small and medium-sized organizations; however, all organizations, independent of size, can use these practices to improve the security of their cloud usage. The focus here is on hybrid deployments where some information technology (IT) applications deploy or move to a CSP while other IT applications remain in the organization's data center. This hybrid deployment model is likely to be the norm for quite some time.

Small and medium-sized organizations likely have limited resources; where possible, these practices describe implementation approaches that may be effective in limited-resource situations.

Prior to describing the practices, we present a few risk examples. These examples describe actual cybersecurity incidents. For each example, there are pointers to one or more practices that, if applied, could have reduced the risk of the incident.

The four important practices are

- **Perform Due Diligence**—Due diligence requires that cloud consumers fully understand the security implications of deploying or moving applications and systems to a CSP. Consumers must understand how CSP services should be used to support business activities while protecting information.

¹ "A mission thread is an end-to-end set of steps that illustrate the technology and people resources needed to deliver expected behavior under a set of conditions and provide a basis for identifying and analyzing potential problems that could represent risks. For each mission step, the expected actions, outcomes, and assets are assembled. Confirmation that the components appropriately respond to expected operational use increases confidence that the system will function as intended even in the event of an attack."
<https://www.acsac.org/2013/program/wips/Woody.pdf>

² The five mission threads were (1) account compromise threat, (2) multi-tenancy with side channel threat, (3) management API vulnerability, (4) self-provision resources and services, and (5) data deletion.

- **Manage Access**—Managing access involves identifying the different categories of users in a cloud-based IT environment, determining the responsibilities of each user category, and ensuring access to resources is controlled in ways that allow users to carry out their responsibilities while protecting resources from inappropriate or unauthorized use.
- **Protect Data**—Protecting data addresses three consumer challenges: (1) preventing the accidental or unauthorized disclosure of data, (2) ensuring continued access to critical data in the event of errors, failures, or compromise, and (3) ensuring deleted data is no longer accessible.
- **Monitor and Defend**—Monitoring and defending requires the CSP and cloud consumer to work together to monitor cloud-based systems and applications to detect unauthorized access to data or unauthorized use of resources.

To illustrate the practicality of these practices, we present examples using cloud services available from one or more of the “big three” cloud service providers—Amazon Web Service (AWS), Microsoft, and Google [AWS 2019a, Microsoft 2019a, Google 2019a]. These are examples only and are not an endorsement of these cloud service providers or their service offerings. Other CSPs offer capabilities similar to those described in these examples.

The examples span the range of cloud service models: infrastructure as a service (IaaS), platform as a service (PaaS), and software as a service (SaaS). Not every practice has examples for all service offerings. However, across all of the practices, there is at least one example for each service model.

2 Risk Examples

The practices presented here address cloud security issues that consumers typically experience. This section presents examples of recent cloud security incidents. Each example includes references to the practices that mitigate the risk of that incident type.

2.1 Unsecured AWS Storage Services

Several instances of unauthorized exposure of data to the Internet have been linked to improperly configuring AWS Simple Storage Service (S3), thus leaving data accessible.

On September 5, 2017, *The Register* reported, “Records of roughly four million Time Warner Cable customers were exposed to the public Internet after a contractor failed to properly secure an Amazon cloud database” [Nichols 2017]. The access policy on an AWS S3 bucket was improperly configured, allowing public access to data in the bucket. Press reports surrounding this incident suggested that misconfiguration of AWS resources by consumers is a common problem. (Practices that would mitigate this risk include Perform Due Diligence, Manage Access, Protect Data, and Monitor and Defend.)

On June 1, 2017, a security researcher found sensitive files openly available on the Internet. The files were stored in plain text in an Amazon S3 bucket with no password protection. Zohar Alon, co-founder and CEO of cloud infrastructure security company Dome9, said, “Yet security of S3 buckets to prevent accidental data exposure is often poorly understood and badly implemented by their users, even someone as technically savvy as an engineer with one of the world’s leading defense contractors” [Barth 2017]. (Practices that would mitigate this risk include Perform Due Diligence, Manage Access, and Monitor and Defend.)

2.2 Deloitte Email Compromise

On September 25, 2017, *The Guardian* reported the global consulting firm Deloitte³ was “... the victim of a cybersecurity attack that went unnoticed for months” [Hopkins 2017]. The attack used a compromised system administrator credential to access the firm’s email system hosted in Microsoft Azure. The administrator account used only a password for authentication. (Practices that would mitigate this risk include Manage Access and Monitor and Defend.)

2.3 Accidental Data Loss

On April 21, 2011, 0.07 percent of data stored in Amazon Elastic Block Storage (EBS) volumes in a US-EAST region availability zone was irretrievably lost [Blodget 2011]. An error in a maintenance procedure caused a significant drop in network bandwidth within an EBS cluster [AWS 2011]. This loss of bandwidth ultimately resulted in a race condition causing EBS cluster nodes to fail. After repairing the EBS cluster, Amazon was able to recover most customer data. However, a small amount of customer data was permanently lost. (Practices that would mitigate this risk include Protect Data.)

³ For information on Deloitte LLP, go to <https://www2.deloitte.com/us/en.html>

2.4 Code Spaces Data and Systems Destroyed

Code Spaces was a CSP that provided SaaS source code management tools such as Git and Apache Subversion to software developers. Code Spaces built its SaaS offering using AWS. In 2014, a Code Spaces privileged user AWS credential was compromised. Within 12 hours of the compromise, most of Code Spaces' data and all of its virtual machines were permanently deleted. Code Spaces lost its customers' data and, as a result, ceased operations [Goodin 2014]. (Practices that would mitigate this risk include Perform Due Diligence, Manage Access, and Protect Data.)

2.5 OneLogin Data Breach

OneLogin is a CSP that provides SaaS Identity and Access Management (IdAM) services to business [OneLogin 2019]. OneLogin's products use AWS. In May 2017, the company reported a hacker obtained access to a set of AWS keys through a third-party vendor. With these keys, the hacker was able to access and compromise all of OneLogin's records at its U.S. data center [Whittaker 2017]. (Practices that would mitigate this risk include Manage Access, Protect Data, and Monitor and Defend.)

3 Shared Responsibility Model in Cloud Computing

CSPs use a shared-responsibility model for security. The CSP accepts responsibility for some aspects of security; other aspects are shared between the CSP and the consumer. Finally, some aspects of security remain the sole responsibility of the consumer. This shared-responsibility model is an example of the three security control types defined by the U.S. National Institute of Standards and Technology (NIST) in Special Publication 800-53r4 [NIST 2013].

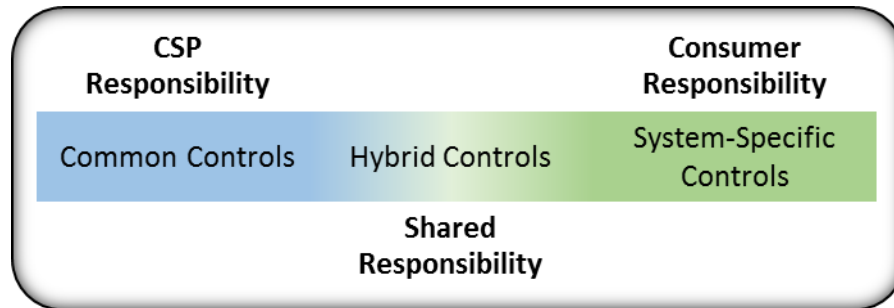


Figure 1: Shared Responsibility for Cloud Security

NIST defines common controls, hybrid controls, and system-specific controls. In cloud computing, *common controls* are the security controls that are fully implemented by the CSP. These controls are inherited by all consumers. Physical security⁴ for the computing infrastructures used to deliver cloud services is an example of a common or CSP-provided security control.

In cloud computing, *hybrid controls* are security controls that are partially implemented by the CSP and partially implemented by the consumer. Controlling access to CSP services by consumer personnel⁵ is an example of a hybrid or shared security control. The CSP provides mechanisms to define and enforce access control policies. The consumer must use these mechanisms to specify which personnel are permitted to access cloud services. The consumer's policies, enforced by CSP mechanisms, implement access control.

In cloud computing, *system-specific controls* are security controls that must be implemented by the consumer. In IaaS and PaaS, collecting auditable events from consumer-implemented applications is an example of a system-specific control.⁶ In SaaS, system-specific controls are likely to be procedural, such as reviewing audit trails and taking corrective action.⁷

Effective cloud security depends on consumers knowing and meeting all their security responsibilities. Consumers who fail to understand or meet their security responsibilities are a leading cause of security incidents in cloud-based systems.

⁴ NIST SP800-53r4 security control PE-3 is an example of a security control provided by the CSP.

⁵ NIST SP800-53r4 security control AC-3 is an example of a security control that, when applied to consumer personnel accessing CSP services, must be partially implemented by the CSP and the consumer.

⁶ NIST SP800-53r4 security control AU-2 is an example of a security control that must be implemented by the consumer as part of applications the consumer develops in IaaS or PaaS.

⁷ NIST SP800-53r4 security control AU-6 is an example of a system-specific procedural security control in SaaS.

The risk example of unsecured AWS storage services in Section 2.1 illustrates a situation where cloud consumers failed to meet their responsibilities, resulting in security incidents. In the September 26, 2017 *SANS Newsbites* [SANS 2017], Alan Paller noted,

Ian Massingham, a technical evangelist at Amazon Web Services (AWS) explained how, for 'infrastructure as a service,' AWS takes no responsibility for secure configuration of the operating system or security monitoring, for application security configuration or monitoring, for account management, for access control lists, for identity management and more [Massingham 2015]. Amazon provides great tools for implementing security controls, but as you'll see in the Amazon video, you must be very skilled to deploy them broadly and effectively [Franz 2016]. One of the least fun jobs at (all of the) cloud service providers is nicknamed 'CAO' for Chief Apology Officer, having to go to clients and explain to them that whatever they heard about cloud security being better, all the responsibility for making that happen rests on the user.

4 Important Practices

The practices presented in this section describe key cloud consumer responsibilities in ensuring the security of cloud-based systems and applications.

4.1 Perform Due Diligence

It's crucial to perform due diligence across the lifecycle of applications and systems being deployed to the cloud. This includes activities in four phases: planning, development and deployment, operations, and decommissioning.

4.1.1 Planning

The first step in a successful cloud deployment is selecting an appropriate system or application to move to, build in, or buy from a CSP. Getting this step right is challenging for a first-time cloud deployment. We recommend that you benefit from the experience of others and use a cloud adoption framework to efficiently use cloud services. A cloud adoption framework provides a process for identifying applications, selecting cloud providers, and managing the ongoing operational tasks associated with public cloud services. Cloud adoption frameworks may be CSP specific or CSP agnostic.

AWS provides a cloud adoption framework that addresses six perspectives: business, people, governance, platform, security, and operations [AWS 2019h]. While this framework is CSP specific, much of the information and advice applies to any cloud adoption, not just AWS.

Cloudyn published a series of three articles, titled *The Cloud Chronicles*, that present a CSP-agnostic adoption framework [Cloudyn 2017].⁸ The framework looks at migrating to the cloud, determining if your application will run in the cloud, choosing a CSP, using multiple CSPs, and determining cloud costs.

A paper by Dargha describes a CSP-agnostic framework consisting of five stages: knowledge acquisition, persuasion, decision, implementation, and confirmation [Dargha 2012]. The paper describes activities for each stage and provides an adoption decision process.

Using a framework helps an organization understand the impact of cloud use. For example, using SaaS can provide value to small or medium-sized organizations with limited IT staff. As another example, providing Outlook email and SharePoint Online using Microsoft Office 365 frees IT staff from installing, operating, and maintaining these services locally. However, the existing business workflows, such as provisioning and deprovisioning users or providing technical support, must change to support the use of Office 365. Additionally, the current fixed costs of providing email and SharePoint become a combination of fixed and variable costs.

After using a cloud adoption framework to identify both a target system or application for cloud deployment and a CSP, all staff involved in the deployment must be educated on the basics of the

⁸ Cloudyn was acquired by Microsoft on July 20, 2017.

selected CSP, the CSP's architecture, the services offered, and the tools available to assist in deployment. Staff members must understand the CSP's shared responsibility model and its impact on their role in the cloud deployment. Having all team members well versed in the basics of the chosen CSP, with emphasis on the other three practice areas, helps to ensure clear communication.

For example, the AWS architecture is a collection of regions with multiple availability zones (AZs) in each region. Services operate and data is stored within regions and AZs. Workloads can be balanced across AZs within a region but not across regions. Team members must understand these concepts to discuss designs and ensure shared and consumer-specific security responsibilities are met.

The availability of applications can be ensured by placing application instances in multiple AZs. Team members must understand these concepts to design and implement applications that meet business availability requirements. Business analysts must be familiar with these concepts to understand how their availability requirements are being satisfied.

For organizations that must comply with industry or government regulations, CSPs may provide guidance on meeting these requirements using their services. For example, AWS provides a "quickstart" guide for United States Federal Government agencies that must comply with the Federal Information Security Management Act (FISMA) requirements in FIPS-199 [NIST 2004] and NIST SP800-53 [AWS 2019f]. Microsoft provides "Azure Security and Compliance Blueprint – PCI-DSS-compliant Payment Processing environments" that provides guidance for meeting Payment Card Industry (PCI) – Data Security Standards (DSS) requirements in an Azure PaaS deployment [Simorjay 2018].

4.1.2 Development and Deployment

Training the development and deployment teams in proper use of CSP services is essential. CSPs provide guidance and documentation on best practices for using their services. If developing a new application or system, follow the CSP's guidance in designing the system or application.

If you are migrating an existing application or system, review its architecture and implementation relative to the CSP's guidance to determine what changes are needed to deploy the application appropriately. It may be necessary to discuss the deployment with the CSP's technical support staff to understand the changes you require.

CSPs provide tools to ensure resilience in the case of failure. Make sure the team knows how to use these tools correctly. In several instances where AWS suffered a service outage, press reports noted that consumers whose applications failed did so because the consumers were not using AWS correctly [Netflix 2011].

CSP services often require specific configurations to provide security. Make sure the team understands these configurations and fully implements them. The incidents of unsecured AWS storage services, described in Section 2.1, were the result of consumers failing to (1) configure the access policy for the storage service correctly and (2) encrypt the stored data. This event reinforces the need for staff to be well trained on the use of CSP resources. To help reduce these errors, AWS recently changed S3 to encrypt data by default [Barr 2017, Coles 2019].

Review the organization's security policies and current security control implementation approaches. Check the CSP's guidance before implementing the on-premises security approach in the cloud. First, verify that, if implemented in the cloud, the on-premises approach would be effective. Then, see if CSP services provide a better implementation approach that still meets security policy goals.

Moving to a cloud environment may present risks that were not present in the on-premises deployment of applications and systems. Check for new risks and identify new security controls that will be necessary to mitigate these risks. Again, consider how CSP-provided control implementations can help.

For example, cloud infrastructure is shared by multiple CSP customers and accessible by CSP administrators. This sharing may increase the risk of unauthorized data exposure and require encrypting data at rest. The CSPs provide tools that can be used to encrypt data. In IaaS and PaaS deployments, the applications that process this data may require modification to properly access and use encrypted data.

Connecting your on-premises IT with cloud-deployed systems and applications changes the risk exposure of those on-premises resources. Review the security controls in place in your on-premises IT environment and ensure those controls adequately address risks once connected to a CSP.

If the CSP provides tools to check for proper and secure configuration of services, use them. AWS provides Quick Start guides that help deploy popular solutions on AWS, based on AWS best practices for security and high availability [AWS 2019c]. Microsoft provides Cloud Infrastructure and Management Practice Accelerators to support development using Azure [Microsoft 2019c].

If using contract resources to migrate an existing application or build a new application using cloud services, the organization's staff must provide effective oversight of the contractor. To provide oversight, staff need both an understanding of the CSP's basic architecture as described in Section 4.1.1 of this report, Planning, as well as a working knowledge of the CSP services being used in the application.

4.1.3 Operations

Once developed and deployed, applications and systems must be operated securely. O'Reilly Media, in describing its book *AWS System Administration* [Lucifredi 2014], says,

Building and deploying infrastructure with Amazon Web Services is simply not the same as dealing with static servers. With tools that let you automatically replace instances and scale up and down in response to demand, it's actually more like programming than traditional system administration.

Unlike physical servers, disks, and networking devices, cloud virtual infrastructure is defined by software. As such, the infrastructure can be treated as source code. Manage the software that defines the cloud virtual infrastructure using a source code control system. Source code control systems have proven effective in managing software development. These same practices can be adapted to manage cloud infrastructure. Use the source code control system to enforce change

control procedures. Changes to production resources should require independent approval prior to implementation.

System administrators must learn to use the CSP's tools to operate systems and applications. Developing new procedures is necessary to address the combination of operational practices for on-premises and cloud-based applications and systems.

The AWS CloudFormation service is an example of infrastructure defined by software. CloudFormation uses templates that describe cloud infrastructure, such as virtual machines and virtual disks that compose a virtual data center. Since these templates are just text files, they can and should be managed and configuration controlled just like other software. System administrators, however, must learn to use the template language effectively and configure resources securely. Additionally, they need clear procedures for when and how to check templates out of/into a source code control system.

Another example is Microsoft Office 365, which provides Admin Center, a web portal accessible to people with admin user accounts. The portal provides access to all configuration, billing, and operation information related to an organization's Office 365 subscription. Links are provided to service-specific admin centers such as Exchange Online, SharePoint Online, and Skype.

Office 365 administrators must understand the options available to them through the various admin centers, the impact of those options on the operation and security of Office 365 services, and their effect on integrating Office 365 with on-premises applications and systems.

4.1.4 Decommissioning

There are many reasons why a cloud-deployed application or system may need to be decommissioned. The CSP could go out of business. The CSP could discontinue key services used by the application. The CSP's prices could increase, making the current deployment too expensive. Whatever the reason, planning for decommissioning a cloud application or system should be done before deployment. Cloud services are currently unique to each CSP. Therefore, moving an application or system from one CSP to another is likely to be a major effort.

Address this risk by developing a multiple-CSP strategy. A CIO.com article provides perspectives on the need for a multi-CSP strategy from several chief information officers (CIOs) [Boulton 2017]. They recommend analyzing how the selected application could be deployed to more than one CSP when making the initial CSP selection. For example, examine how the application or system could be deployed to AWS and to Microsoft Azure. Both AWS and Microsoft Azure have significant overlap in the types of services offered, although details of each offering differ.

Mappings among CSPs, readily available on the Internet, can help identify how an application architected for one CSP might be moved to another [Comparecloud.in 2018]. While the application or system may be deployed to only one of these CSPs, it makes sense to track aspects of the deployment that are unique to the chosen CSP and would require redesign if moved.

In addition to determining how to deploy to multiple CSPs, consider what would be involved in leaving a CSP. The most important part of any application or system is the data stored and processed within. Therefore, it is critical to understand how the data can be extracted from one CSP and moved to another. This extraction can be difficult with many cloud service models. Even for

those—like IaaS, where the consumer has substantial control over how and where the data is stored and has the ability to develop software that can extract the stored data—cost may be a major issue. CSPs typically charge for transfers of data into and out of their services. To incentivize use of CSP services, these charges may be asymmetric—lower for transfer into the CSP and higher for transfers out of the CSP.

SaaS presents a particularly significant challenge since the consumer’s data is stored by the CSP where and how the CSP chooses. To move data from one SaaS offering to another, the consumer is solely dependent on the source CSP providing a data extraction tool that exports data in a format that can be ingested by the destination CSP. It is best to know how to do this before storing years of data in a CSP’s SaaS application.

Gartner presents a three-step strategy for addressing SaaS CSP exit planning in a report titled *Plan Your Data Exit Strategy Before You Sign a SaaS Contract* [Dayley 2017]. Gartner advises consumers to “. . . test data movement into and out of the cloud during proof of concept, negotiate cloud contracts to allow for easy data extraction, . . . establish migration skills, and develop an internal competency on data availability.”

The Microsoft Dynamics CRM team blog has an article that describes exporting data from Salesforce.com and then importing the data to Microsoft Dynamics [Microsoft 2009]. While the article makes the process seem simple, there are hints that this can be a tedious undertaking. For example, only certain Salesforce service tiers can perform a full data export. Other service tiers need to generate and export reports in Salesforce that can be used for import. In this case, the burden of ensuring all data and relationships among data items are exported belongs to the user, not the CSP.

Business Continuity Planning and Disaster Recovery Planning are related to migration from one CSP to another. With applications and systems hosted at CSPs, these plans must address threats to organization data and services at the CSP. Recovery could potentially involve bringing an application or system back on premises or migrating to another CSP.

4.1.5 Key Considerations

Below are the key considerations for performing due diligence:

- Use a cloud adoption framework to identify cloud-appropriate applications and select a CSP.
- Thoroughly train staff in the architecture, use, and operation of CSP services.
- Use a source code control system and change control procedures to manage cloud resource configuration.
- Plan for extracting data and moving applications from the chosen CSP to another CSP or back on premises before deployment.

4.2 Manage Access

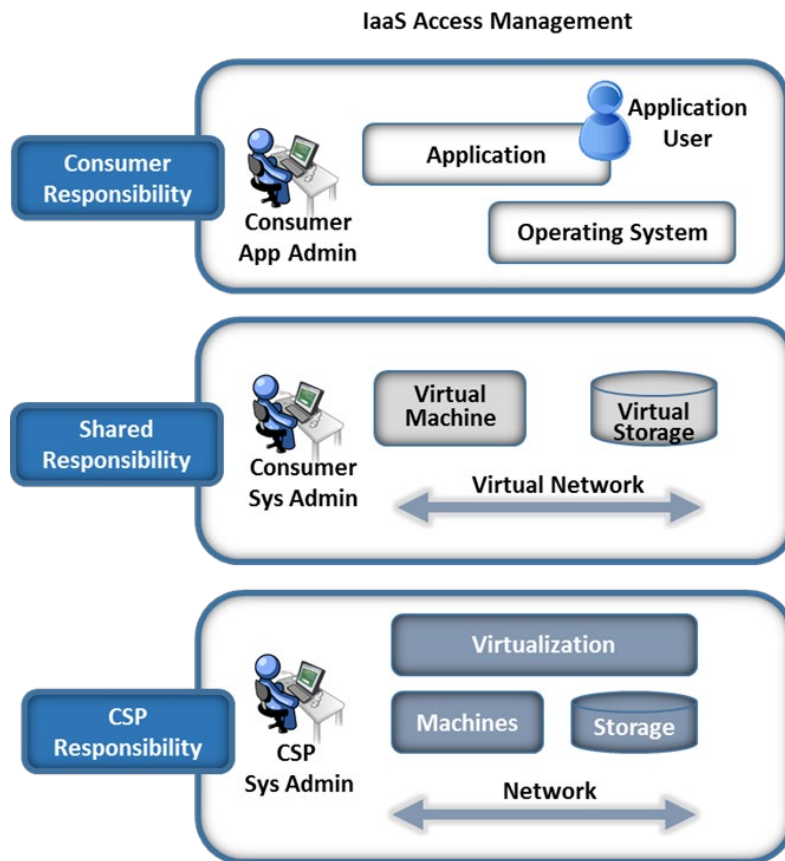


Figure 2: IaaS Access Management and Shared Responsibility

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As described in Section 3, security in cloud computing is a responsibility shared by the CSP and the cloud consumer. Figure 2, derived from work by The MITRE Corporation, illustrates this shared responsibility in managing access to IaaS resources [Faatz 2017]. The CSP is fully responsible for managing access to physical resources such as computers, network storage devices, and the virtualization system that provides service to consumers.

Access to create, manage, and destroy virtual resources such as virtual machines and virtual storage is a shared responsibility. The consumer must define the policy that determines who has access to perform these actions. The CSP must provide mechanisms to enforce the consumer's policies.

Access to applications and operating systems is solely the responsibility of the consumer, who must both define access policies and put mechanisms in place to enforce those policies. Control of access to resources is not complete without implementing all three parts correctly and completely.

Managing access to resources determines who can access them and what they can do with the resources they can access. Access management generally requires three capabilities: the ability to

identify and authenticate users, the ability to assign users access rights, and the ability to create and enforce access control policies for resources.

4.2.1 Identify and Authenticate Users

The starting point for access management is identifying and authenticating users. Legitimate users are given credentials that bind their identity to an authenticator. The most common credential is a username and password, the password being something only the user knows.

One of the most effective ways of attacking an organization's information systems is to gain access using legitimate user credentials, especially privileged user credentials. Such credentials can be particularly valuable in accessing cloud services, since management interfaces are accessible from the Internet. While an organization may use a private connection to the CSP, the management interfaces used by customers are also available via the Internet. With stolen privileged user credentials, an attacker can control and configure cloud consumer resources.

The Deloitte email compromise and the OneLogin data breach described in the Risk Examples, Sections 2.2 and 2.5, both demonstrate attacks using compromised credentials. As in the Deloitte case, these breaches often go undetected for months, since all access appears to be performed by legitimate, authorized users. Credentials that depend solely on something the user knows, such as passwords, are particularly susceptible to theft since there is no obvious way for the legitimate user to know the credential has been compromised.

To reduce the risk of credential compromise, use credentials that employ multiple factors to authenticate users (multifactor authentication or MFA). MFA reduces the likelihood of a credential compromise because it requires an adversary to acquire multiple, independent elements to compromise a credential. In cloud computing, MFA typically combines a password with something the user has, such as a text message sent to a previously registered cell phone. This second factor makes credential compromise more difficult and more likely to be detected quickly. Many cloud providers offer MFA capabilities.

Compromise of privileged user credentials is particularly concerning since these credentials allow the user to manage the IT environment. With the right privileged user credentials, an attacker can more easily achieve persistent access by installing software or creating user accounts. If it is not practical to use multifactor credentials for all users, start with privileged users.

Microsoft, for example, supports Azure multifactor authentication for Office 365 users. This authentication is easily enabled in the Office 365 Admin Center [Microsoft 2019d]. On users' first or next login, they are asked to complete MFA registration by providing a phone number and specifying whether a text message or phone call should be used as a second factor.

AWS offers several MFA options as well [AWS 2019e]. The simplest option is similar to Microsoft Azure multifactor authentication via the user's cell phone. However, AWS also offers extra-cost options using special hardware tokens.

CSPs typically provide a consumer with an initial privileged credential that can perform all privileged operations. This credential is similar to a "root" credential in Linux or an admin credential in Windows. However, the scope of privilege associated with this credential is much broader than control over one or more machines. This credential is the logical equivalent of granting unfettered

access to a physical data center. In IaaS, this credential allows the creation and destruction of virtual machines, virtual disks, virtual networks, and other privileged user accounts.

Compromise of this credential gives an attacker the ability to control a consumer's cloud resources. An attacker could prevent a consumer from accessing his or her cloud resources or delete the consumer's data. Do not routinely use this initial credential to manage virtual resources. Routine use of this credential increases the consumer's exposure to compromise. Use this credential ONLY to define and set up the initial set of users and roles.

Privileged user credential compromise can be devastating. A privileged user credential compromise, as described in the risk example Code Spaces Data and Systems Destroyed, in Section 2.4, caused Code Spaces to go out of business.

4.2.2 Assign User Access Rights

Plan a collection of roles to satisfy both shared and consumer-specific responsibilities. CSPs and others, such as Gartner, provide advice on designing roles [Microsoft 2017, Gartner 2016]. These roles should, to the extent feasible, ensure that no one person can adversely affect the entire virtual data center. In a traditional data center, this separation might take the form of defining separate operating system, storage, and network administrators. However, since all of these resources are virtual in an IaaS cloud and can be managed by writing code, a strategy that separates defining resources from deploying defined resources to production might be more effective.

Individual developers and system managers should not have uncontrolled access to resources. Limiting access can constrain the impact of a credential compromise or a malicious insider. Developers should be constrained to assigned projects. System managers should be constrained to assigned resources. CSPs may provide guidance on appropriate roles and privileges for managing services. When establishing roles, apply the principle of least privilege. Give roles only those privileges explicitly needed to perform their function. Similarly, give services and applications only those privileges needed to operate. Service and application roles should not have elevated privileges.

CSPs offer a variety of ways to implement credential and user access management. One approach defines all users, credentials, and roles in the CSP's system. These are completely disjoint from on-premises users, credentials, and roles. A second approach extends all or part of the on-premises Active Directory (AD) into the cloud environment. A third approach uses the existing on-premises users and credentials, augments them with roles and groups appropriate to the cloud environment, and federates the cloud environment with the on-premises capabilities. Each of these approaches has strengths and weaknesses that warrant consideration in an organization-specific context.

Managing users, credentials, and roles for access to cloud services entirely in the cloud ensures there is no unintended crossover of users from the on-premises environment to the cloud environment. However, it can result in operating two independent identity and access management processes. It can also complicate the user experience, as users have separate credentials for cloud and on-premises access. This separation is appropriate for privileged users who create, manage, and destroy virtual resources in the cloud.

Extending all or part of the on-premises AD into the cloud can consolidate identity and access management for both cloud and on-premises users in a single set of processes. This consolidation ensures a single, consistent approach to access management. This approach may be appropriate for application users as it provides the same user experience across on-premises and cloud-deployed applications. However, this approach also potentially exposes the on-premises AD to cloud-based threats. When using this approach, ensure the security controls protecting on-premises AD instances are effective against these additional threats.

To provide further control of privileged user access to operating systems and applications running on virtual machines, use bastion hosts.⁹ Using bastion hosts is a best practice for both on-premises and cloud-deployed systems. Bastion hosts are a form of proxy that is interposed between a privileged user and the operating systems and applications they manage. The bastion host determines which systems and applications a privileged user can access and what operations the privileged user can perform on those resources. Additionally, the bastion host maintains a dedicated log of privileged user actions, making it easier to review those actions for indicators of inappropriate privileged access.

The Best Practice Guide for Department of Defense Cloud Mission Owners provides guidance on implementing bastion hosts in IaaS cloud deployments [DISA 2015]. AWS provides a Quick Start template that builds a simple Virtual Private Cloud (VPC) architecture incorporating bastion hosts [AWS 2017]. This AWS example can be adapted to other IaaS providers.

Apply configuration management to access permissions for users and roles. This will help prevent accidental or malicious changes to access permissions. Incorporate separation of duties in the configuration management process to prevent any one person from both approving access permission changes and implementing the changes. Periodically review access permissions to ensure users still need their assigned roles and roles still require their configured permissions. Cloud access security broker (CASB) technology is a growing market that could help organizations automate enforcement to prevent incidents, such as the Deloitte email compromise and the OneLogin data breach risk examples, and simultaneously reduce burden on IT staff.

4.2.3 Create and Enforce Resource Access Policies

Cloud services may require service-specific access policies. The unsecured AWS storage services risk example in Section 2.1 resulted from improperly configured AWS S3 access policies. It is important to understand access policy configuration requirements associated with cloud services. Additionally, consumers must be aware of updates to cloud services that affect access policy configuration. Upgrades to or maintenance of cloud services can add, remove, or change access policy parameters.

CSPs offer many storage service types such as virtual disks, blob storage, and content delivery services. Each of these has unique access policies that must be configured to protect the data they store.

As an example of all the actions a consumer should take to manage access, AWS provides recommendations for AWS identity and access management [AWS 2019d]. While the recommendations

⁹ Information on the use, construction, and hardening of bastion hosts can be found at the SANS website, <https://www.sans.org/reading-room/whitepapers/basics/hardening-bastion-hosts-420>

are specific to AWS, the underlying actions are applicable to many CSPs. Additional identity and access management recommendations are provided by Microsoft and Google as well [Microsoft 2019b, Google 2019b].

4.2.4 Key Considerations

The key considerations for managing access are below:

- Use multifactor authentication.
- Implement a collection of roles that provide separation of duties.
- Ensure access policies are properly configured on all storage services.

4.3 Protect Data

To protect data, develop a data protection strategy that addresses both on-premises data and cloud data. Conduct periodic assessments to verify procedures are in place that implement the strategy.

Protecting data involves three separate challenges: (1) preventing unauthorized access, (2) ensuring continued access to critical data in the event of errors and failures, and (3) preventing the accidental disclosure of data that was supposedly deleted.

4.3.1 Prevent Unauthorized Access

As mentioned previously, the unsecured AWS storage services risk example in Section 2.1 resulted from incomplete or missing AWS S3 access policies. This oversight allowed unauthorized access to the data stored in the S3 buckets. However, if the data in the S3 buckets had been encrypted, this unauthorized access would not have disclosed the stored data. Data at rest should be encrypted to protect against disclosure due to unauthorized access.

AWS provides multiple options to encrypt data stored in S3 and other data storage services. Similarly, other CSPs provide encryption capabilities for their storage services.

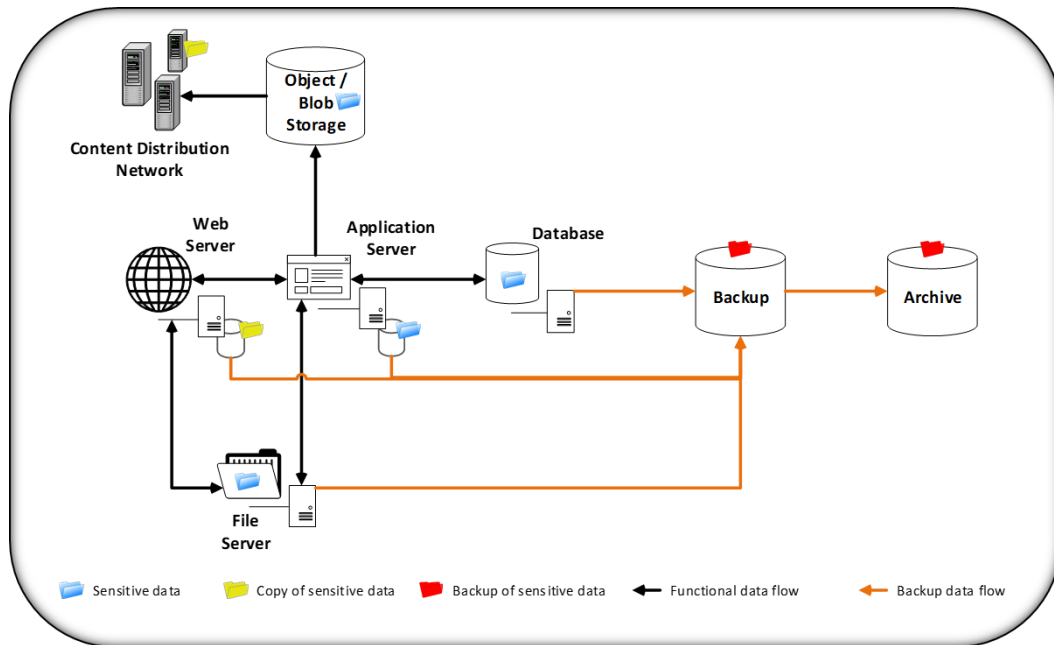


Figure 3: Sensitive Data in a Typical Cloud Web Application

Encrypting cloud data at rest may involve encrypting the data in multiple cloud services. Figure 3 shows the architecture of a typical web application deployed to an IaaS CSP. Sensitive data that needs protection spreads throughout the IaaS environment. The data is initially located in the file server, the application server, the object/blob storage, and the database as shown by the blue folders. As the data is accessed, it spreads to the web server and the content delivery network shown by the yellow folders. To protect availability, the data from the file server, application server, and database is copied to the backup service. Backups are eventually rolled off to an archive service. Backups and archives are shown by red folders.

To protect the sensitive data, analyze the cloud deployment thoroughly to understand where sensitive data may have been copied or cached. You must understand and use the encryption capabilities of all the services to which data may have been copied to ensure that, no matter where the data is stored, it is protected.

Of course, encryption is only effective if the associated encryption keys are well managed. CSPs offer consumers a choice of CSP-managed or consumer-managed keys. CSP-managed keys are convenient but provide the consumer no control over where or how the keys are stored. Consumer-managed keys place the burden of key management on the consumer but provide better control [Chandramouli 2013, Snedeker 2017]. Consumer-managed encryption keys should not be stored in the cloud with the data they protect. Doing so increases the risk of key compromise and unauthorized access to data. To address this risk, CSPs offer hardware security modules (HSMs) to help consumers securely manage keys. An HSM is a hardware device that the CSP provisions into the consumer's environment. Consumers have full control of the HSM, ensuring that only they can manage the keys stored there. For example, Microsoft Azure offers the Azure Key Vault HSM [Plastina 2015].

4.3.2 Ensure Availability of Critical Data

CSPs provide significant guarantees that persistent data will not be lost. However, no system is perfect, and major cloud providers have accidentally lost customer data. For example, the accidental data loss risk example in Section 2.3 describes an incident in which AWS permanently lost consumer data from some Elastic Block Storage (EBS) volumes.

In addition to CSP errors, cloud consumers may also make mistakes that result in data loss. Therefore, it is important to understand CSP data backup and recovery processes to ensure they meet the organization's needs. The organization may need to augment CSP processes with additional backup and recovery actions. CSPs provide services that consumers can configure to perform backup and recovery operations.

In the data loss risk example cited above, Amazon recommended that consumers restore data from their own backups. AWS provides the ability to snapshot EBS volumes to S3 as a means of backing up the EBS volumes. Additionally, S3 data can be migrated to near-line storage in Amazon Glacier¹⁰ to back up the S3 data while reducing storage costs.

As with on-premises backups, cloud consumers must determine the criticality of data and ensure that appropriate backups are performed—by the CSP, jointly by the CSP and consumer, or by the consumer alone.

The Code Spaces Data and Systems Destroyed risk example, in Section 2.4, illustrates the importance of determining data criticality and ensuring appropriate backups exist to support business continuity. In this case, apparently Code Spaces was entirely dependent on backups maintained in AWS along with its production infrastructure. A single compromise destroyed the data that was critical to its business. Without that data, there was no business, and Code Spaces ceased operation. Given the criticality of the data, a backup strategy using a second CSP or on-premises storage would have been prudent.

Rackspace published the white paper *Best Practices for Cloud Backup* [Hendler 2016]. This paper discusses what to back up, how to conserve resources with cloud backup, and frequently encountered issues. While this paper targets consumers of Rackspace's cloud and hosting services, you can adapt the concepts and information to other providers.

As mentioned in Section 4.1, Perform Due Diligence, ensuring access to consumer data in SaaS deployments is particularly challenging. For example, with a SaaS email system, all of the consumer organization's email is stored in CSP systems. There may not be an effective approach for the consumer to back up this email or extract it from the CSP's system. In SaaS, unless the provider offers a way to export the data, consumers have no means of independently backing up the data or migrating it to another application. As discussed previously, it's important to develop plans for extracting data from SaaS applications before adopting the service.

4.3.3 Prevent Disclosure of Deleted Data

While a cliché, the phrase “the Internet never forgets” is relevant to cloud-based storage. Cloud storage services replicate data to ensure persistence. As Figure 3 illustrates, during the course of

¹⁰ “Amazon Glacier is a . . . durable, extremely low-cost cloud storage service for data archiving and long-term backup.” <https://aws.amazon.com/glacier/>

system operation, sensitive data can find its way into logging and monitoring services, backups, content distribution services, and other places. When sensitive data must be deleted, or resources containing sensitive data are retired, the replication and spread of data through services during normal system operation must be considered.

Analyze the cloud deployment thoroughly to understand where sensitive data may have been copied or cached and determine what must be done to ensure these copies are deleted. Some services may retain data for defined retention periods following deletion to prevent accidental loss of data. For these services, validate that the data is actually deleted following the retention period.

Data is ultimately stored on media such as magnetic or solid-state disks. These media devices can and do fail regularly and must be replaced. Even though the device itself has failed, consumer data still resides on the device. It is important to understand how the CSP handles storage media removed from production. AWS, for example, destroys all media removed from service. Other providers may choose to sanitize magnetic media using degaussing or other methods.

Encrypting data at rest, as described in Section 4.3.1, ensures that, even if data is not fully deleted or the storage media fails and is not destroyed or sanitized, the residual data is not usable.

4.3.4 Key Considerations

These are the key considerations for protecting data:

- Encrypt data at rest.
- Determine the criticality of data to business operations and ensure appropriate backups are performed.
- When removing data, delete the data from cloud storage services and all other cloud services that have copied or cached the data.

4.4 Monitor and Defend

Figure 4 illustrates the CSP and consumer responsibilities for monitoring when systems and applications are deployed to an IaaS or PaaS CSP.¹¹ Cloud deployment adds complexity to monitoring. To effectively monitor and defend cloud-deployed systems, consumers must learn to use monitoring information provided by the CSP, augment CSP monitoring information where necessary, analyze both cloud and on-premises monitoring data, and collaborate with CSP security operations staff to resolve incidents.

¹¹ A SaaS deployment likely does not have consumer monitoring responsibility in the cloud. Instead, the consumer is responsible for analyzing data provided by the CSP and responding to inappropriate or unauthorized use.

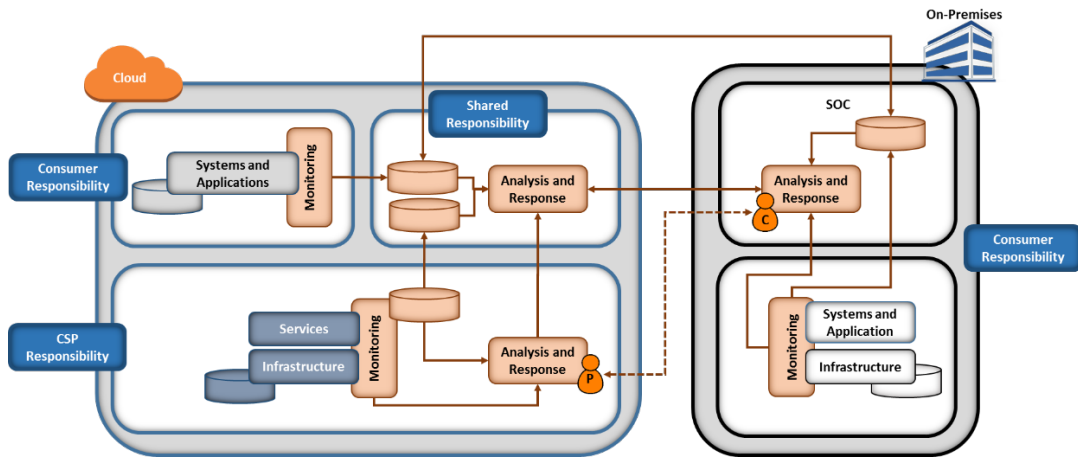


Figure 4: IaaS and PaaS Monitoring Responsibilities

4.4.1 Monitoring Cloud-Deployed Resources

The CSP is responsible for monitoring the infrastructure and services provided to consumers. The consumer is responsible for monitoring the systems and applications created using the provided services. A CSP builds significant instrumentation into its cloud services. A CSP needs this instrumentation to provide metered service, one of the five essential characteristics of cloud computing [Mell 2011], and to defend the infrastructure and services it operates.

From this instrumentation, the CSP provides monitoring information to the consumer that is related to the consumer's use of cloud services. This CSP-provided information is the first line of monitoring to (1) detect inappropriate or unauthorized access to or use of systems and applications, (2) detect unexpected behavior or use of the systems and applications, and (3) identify the users involved. For this monitoring to be effective, the consumer must profile his or her system, services, and data usage. Once a profile of normal operations is established from the CSP monitoring data, the consumer can use the CSP-provided monitoring information to identify unexpected or inappropriate activity.

AWS, for example, provides the CloudTrail service, which captures information on all AWS API calls within a consumer's AWS resources. CloudTrail records the action requested, who requested the action, and the result of the request. Tools for searching and examining CloudTrail records are also provided. AWS can deliver CloudTrail data to an S3 storage bucket where a consumer can use other tools, customer provided or commercially available, to further analyze the information. Monitoring and analyzing CloudTrail logs must be a routine part of operating AWS-deployed systems and applications.

Microsoft Office 365 provides audit log reports, through Security Center, that contain information on user and administrator activities in Exchange Online, SharePoint Online, OneDrive, and Azure Active Directory. These reports can be queried using tools in the Office 365 Security and Compliance center to look for unusual or suspicious activity related to a consumer's Office 365 services.

CSP-provided monitoring data is obviously different from the data collected in on-premises monitoring. Therefore, consumers must learn how to use the new data to defend their cloud-based assets. This involves understanding what the data means, determining what is normal for the cloud

deployment, and learning to use tools provided by the CSP to detect anomalies. The SANS Reading Room contains a variety of short papers that address using CSP-provided data to effectively monitor cloud deployments. For example, a paper titled *Cloud Security Monitoring* explains how to use Splunk to ingest and analyze AWS CloudTrail data [Balakrishnan 2017].

Traditional security product vendors are also developing and selling virtual versions of their products that are already integrated with CSP services. These products can save time and are often already automation-aware. For example, Cisco has extended its on-premises Stealthwatch product to support AWS, Google Cloud Platform, and Microsoft Azure [Cisco 2019]. Stealthwatch uses CSP-provided monitoring data, such as CloudTrail in AWS, to develop models of cloud resources. Stealthwatch then uses these models to monitor resource behavior and detect suspicious activity.

CSPs are also beginning to automate some aspects of monitoring and detection. AWS recently introduced the Macie service, which monitors access to data stored in S3 buckets, develops patterns of expected access, and provides alerts when accesses occur that are inconsistent with historic patterns [AWS 2019b]. Macie automates the determination of normal access patterns and eliminates the need for the consumer to monitor and analyze S3 accesses. Macie may have identified the unauthorized S3 access described in the unsecured AWS storage service risk example in Section 2.1. If Internet access to the S3 buckets were not routine, it would not be included in Macie's access model and could generate an alert when it occurred.

Google developed the Stackdriver service, which can analyze Google Cloud Platform monitoring data as well as AWS monitoring [Google 2019c].

Consumers should focus on using CSP-provided monitoring tools and data. Consumers can augment CSP-provided monitoring data with monitoring of the systems and applications they operate using cloud services. Be aware, however, that monitoring approaches used on premises may not work in the cloud. For example, virtual routers do not provide virtual span ports that can see all network traffic.

Further, on-premises techniques that do work may not be practical. The dynamic nature of cloud services, automatically scaling up and down horizontally, may confuse on-premises monitoring techniques. Design and implement cloud application monitoring carefully to ensure it is fully integrated with cloud automation (e.g., autoscaling in IaaS) and can be scaled up or down without manual intervention. Again, the SANS Reading Room offers CSP-specific advice and examples such as *Packet Capture on AWS* [Radichel 2017].

If bastion hosts are used to manage privileged user access to operating systems and applications as recommended in Section 4.2.2, they can also provide monitoring data that augments CSP-provided data. CSP data can show that a user connected to the bastion host. It can also show that the bastion host connected to an operating system instance or an application. It cannot show what the user did over the connection. The bastion host's log information, however, can show the commands that were performed by the user on the operating system or application.

4.4.2 Analyze Both Cloud and On-Premises Monitoring

With a hybrid cloud deployment that moves some resources to a CSP but retains many resources on premises, CSP-provided monitoring information, consumer cloud-based system and application monitoring information, and consumer on-premises monitoring information must be combined to create a complete picture of the organization's cybersecurity posture. Figure 4 shows a cloud-based monitoring and analysis enclave where all three monitoring data sources are combined.

While this enclave could be placed within the cloud or on premises, there may be advantages to a cloud deployment. First, as mentioned in Section 4.1.4, CSPs charge for data transfers into and out of their services. To encourage a continuing and potentially growing use of their services, CSPs often charge more for transfers out of the cloud than they do for transfers into the cloud. Therefore, depending on the volume of data involved, it may be cheaper to move data from on-premises monitoring into the cloud than it is to move cloud-based monitoring data out to an on-premises enclave.

Second, storage for large volumes of data may be cheaper in the cloud, especially storage for archived data that is being preserved but not actively used. Lastly, consumers can benefit from the inherent elasticity of the cloud, rapidly increasing analysis capacity when needed and decreasing capacity to save money when it is not needed.

Again, tools like Cisco Stealthwatch, mentioned previously, which can be deployed both on premises and in the cloud, may help analyze combined monitoring data.

4.4.3 Coordinate with CSP

The CSP is responsible for monitoring the infrastructure used to provide cloud services. That infrastructure could be physical servers, virtualization software, networks, and storage with IaaS, or entire applications with SaaS. Figure 4 shows a dashed line between the CSP's security analyst (P) and the consumer's security analyst (C).

The CSP may detect events that could adversely affect the consumer's applications. If so, the CSP informs the consumer and coordinates a response. Similarly, the consumer may detect adverse events and need CSP assistance to investigate. As with all aspects of cloud computing, responding to security events is a shared responsibility.

Learn to collaborate with the CSP to investigate and respond to security incidents. To collaborate effectively, the consumer must understand what information the CSP can share, how the information is shared, and the limits within which the CSP can provide assistance. The CSP cannot share information about another customer or provide assistance that would affect another consumer's use of services. Update standard operating procedures (SOPs) to include collaboration with the CSP.

Finally, there are monitoring activities conducted on premises that should not be performed in the cloud without first consulting with the CSP. For example, conducting a vulnerability scan of cloud-based resources may look like an attack to a CSP. In response, the CSP may disable connectivity to the consumer's resources until it contacts the consumer to resolve the issue. Such a

situation could create a self-induced denial of service for the consumer. Consumers must understand what activities may look suspicious to the CSP and pre-coordinate these activities to avoid unnecessary response actions by the CSP.

As an example, Amazon's Acceptable Use Policy prohibits “. . . attempting to probe, scan, or test the vulnerability of a System . . .” [AWS 2016]. However, Amazon also recognizes that organizations should conduct vulnerability scans and penetration testing of their infrastructure as part of a robust cybersecurity program. Therefore, Amazon provides a means for its customers to request permission to conduct this type of testing [AWS 2019g].

4.4.4 Key Considerations

Below are the key considerations for monitoring and defending cloud deployments:

- Use CSP-provided information and services as the primary cloud monitoring mechanism. Augment CSP capabilities only where necessary.
- Combine information from both cloud and on-premises monitoring to provide complete security situational awareness.
- Coordinate with the CSP to investigate and respond to incidents.

5 Conclusions

Cloud services can provide equivalent or better security than most organizations achieve for their on-premises applications and data stores. To achieve these results, organizations must understand and meet their security responsibilities for using their CSP's services. While potential cloud consumers often worry about the security risk of trusting a CSP to perform some security functions, experience shows that security incidents are more often the result of consumers failing to use the security tools provided.

This report describes four important practices that cloud consumers should follow:

1. Perform Due Diligence
2. Manage Access
3. Protect Data
4. Monitor and Defend

A common theme across these practices is the need for cloud consumers to develop a deep understanding of the services they are buying and to use the security tools provided by the CSP. Incidents like the unsecured AWS storage servers, Deloitte email compromise, and OneLogin data breach would most likely have been avoided if the cloud consumers had used security tools such as correctly configured access control, encryption of data at rest, and multifactor authentication offered by the CSPs.

Cloud computing is a new approach to computing that uses some of the pieces and parts that make up on-premises computing. It is naïve and risky to assume that cloud computing works just like on-premises computing, can be secured using the same solutions used on premises, or is fully secured by the CSP.

Like any new technology or approach, using cloud computing effectively and securely requires knowledge and practice. For small and mid-sized organizations, use of well-established, mature CSPs also helps reduce the risks associated with transitioning applications and data to the cloud.

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13. ABSTRACT (MAXIMUM 200 WORDS) This report presents four important security practices that are practical and effective for improving the cybersecurity posture of cloud-deployed information technology (IT) systems. These practices help to address the risks, threats, and vulnerabilities that organizations face in deploying or moving applications and systems to a cloud service provider (CSP). The practices address cloud security issues that consumers are experiencing, illustrated by several recent cloud security incidents. The report demonstrates the practices through examples using cloud services available from Amazon Web Service (AWS), Microsoft, and Google. The presented practices are geared toward small and medium-sized organizations; however, all organizations, independent of size, can use these practices to improve the security of their cloud usage. The focus here is on hybrid deployments where some IT applications deploy or move to a CSP while other IT applications remain in the organization's data center. Small and medium-sized organizations likely have limited resources; where possible, these practices describe implementation approaches that may be effective in limited-resource situations.				
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