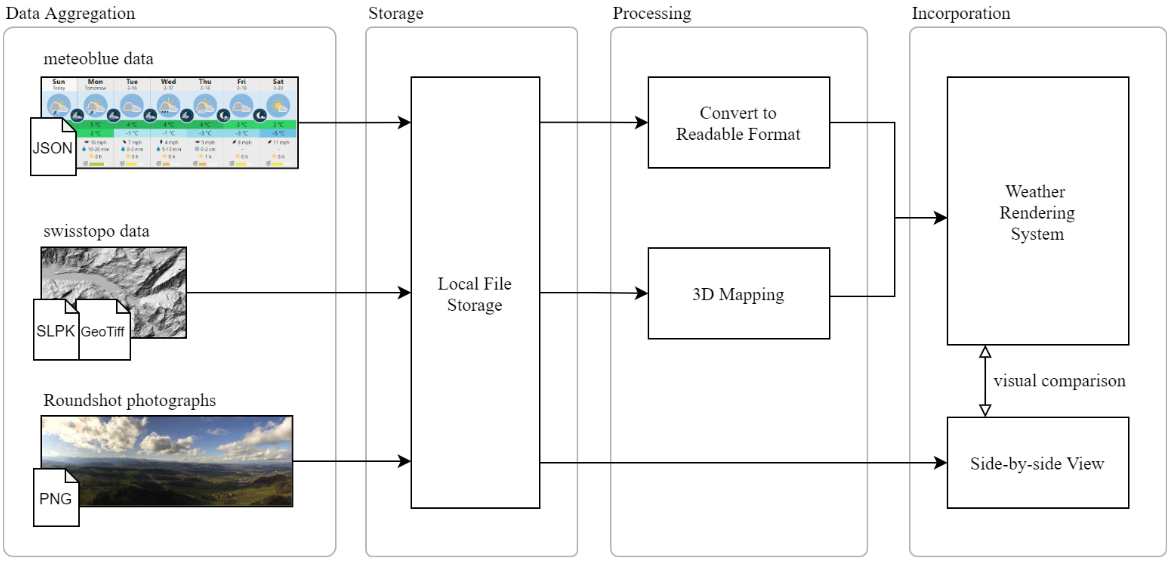
Real-time Weather Rendering System

Project documentation



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Abstract

Clouds contribute a great deal to the overall ambience in games and can be the cherry on top by filling the sky with life. To get as close as possible to real clouds, this project engages in researching and prototyping a procedural, volumetric cloud shader.
In order to achieve volumetric rendering, the document dives into the concept of ray marching, a group of methods used to render a 3D data set inside a container box to make it appear volumetric. Several variants of it are expanded on, like constant step, traditional, and sphere-traced ray marching. Additionally, to account for perception of depth, the volume can be shaded with the aid of surface normal estimation.
In the second part, 2D and 3D noise generation algorithms like Perlin's noise and the Voronoi algorithm are explained in detail. With fractal Brownian motion, the different layers of noise are then merged into one highly detailed noise texture.
At last, the goal of the project was to create prototypes in Unity displaying both volumetric rendering and noise algorithms, of which all were created successfully. Prepared with the combined knowledge of the research results and prototypes, a final shader was created, able to render a completely procedural and volumetric cloudscape.
For future work, the shader could be expanded into a fully-fledged weather simulation system with meteorologically accurate formation of clouds, rain, snow and much more.

Contents

1 General

1.1 Purpose

During this project, all gathered information and knowledge about the researched algorithms and techniques are written down. All prototypes and the final results are documented and compared with real photographs of clouds.

1.2 Audience

This document is written with the intent to further expand existing knowledge about the topic, hence it requires a fundamental knowledge about computer graphics and rendering.

1.3 Revision History

Version	**Date**	**Name**	**Comment**
0.1	March 25, 2020	Matthias Thomann	Initial draft
0.2	April 05, 2020	Matthias Thomann	Cloud classification added
0.3	April 11, 2020	Matthias Thomann	Weather fronts added

2 Natural Clouds

Clouds are a substantial part of Earth's weather. They provide shade from the glistening sun on hot days and reflect the heat at night, keeping the ground warmer. Even for a layman, clouds are comprehensible and useful indicators for telling the weather. If they are dark and low-hanging, they usually bring rain. If they are puffy and scarce, they predict fair weather ahead.

2.1 Convection

In meteorology, convection describes the event of atmospheric motions in the vertical direction. Hot air rises from Earth's surface in form of bubbles, which are called *thermal columns* or just *thermals*. As the altitude increases, the thermal's air cool down. At some point, the warm air diluted by the surrounding colder air, after which its moisture condenses and starts forming clouds [1].

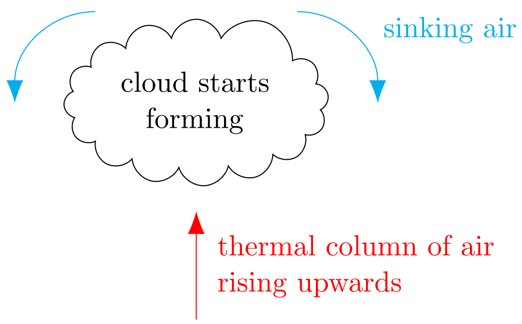

Figure 1: Lifting by convection.

Typically, the sun thermal columns occur when sunlight is warming the ground, and thus the air directly above it. However, it can also be produced by the movement of weather fronts.

2.2 Weather Fronts

According to *metoffice* [2], weather fronts are boundaries between two air masses. Those masses differ in temparature, wind direction and humidity. There are three major types of weather fronts: *warm*, *cold* and *occluded* fronts.
In the following graphics, the warm front is marked with w_1, while the cold front is marked with c_1.

2.2.1 Precipitation Along a Warm Front

When a warm front approaches a cold front, it is likely that the pending clash results in clouds, bringing precipitation . The warm front carries warmer air and therefore rises over the colder, denser air. By advancing towards a cold front, the warm front pushes its warmer air higher, which means that thermals are created and clouds start to form [3].

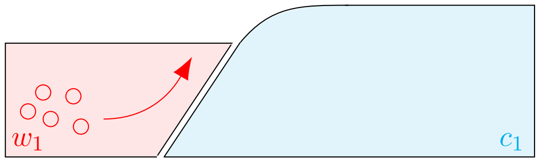

Figure 2: Warm front: Warmer air advances, rising over the colder air, cooling down in the process.

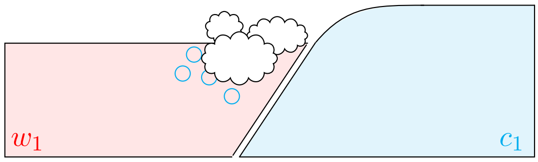

Figure 3: Warm front: As the air cools down, the moisture condenses. Clouds start to form.

2.2.2 Precipitation Along a Cold Front

A cold front represents the boundaries of an air mass carrying cool air. Like to the warm front movement, a cold front catching on a warm front can just as much produce clouds with precipitation. When trailing a warm front, thermals are produced in a similar way. As colder air is denser than warmer air, it pushes underneath the warmer air. By pushing up warm air, that air cools down as it rises, thus clouds start to develop [4].

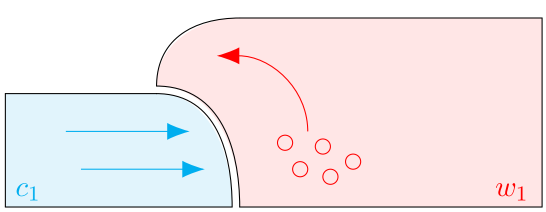

Figure 4: Cold front: Colder air advances, pushing the warmer air upwards, cooling it down.

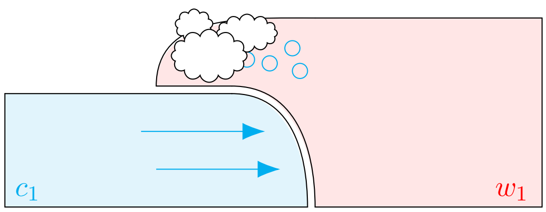

Figure 5: Cold front: As the air cools down, the moisture condenses. Clouds start to form.

2.2.3 Precipitation Along an Occluded Front

There is also the phenomen of front occlusion, producing *occluded front*. This happens when there is a warm front that is caught in the middle of two faster moving cold fronts. At some point, the preceding cold front overtakes the warm front and forces it upwards, causing thermals of warm air rising. Depending on which of the two cold fronts is colder, the outcome may change. The milder cold front is denoted with c_1, while the other cold front with much cooler air is denoted with c_2.
If the preceding cold front carries cooler air than the succeeding, the occlusion is called a *cold occlusion* [5].

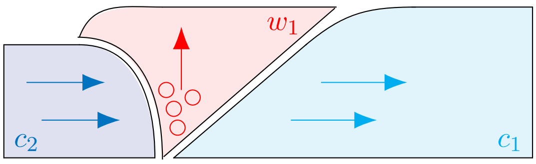

Figure 6: Cold occlusion: Cool air catches up with a preceding cold front, forcing the warmer air inbetween to go up, creating a thermal.

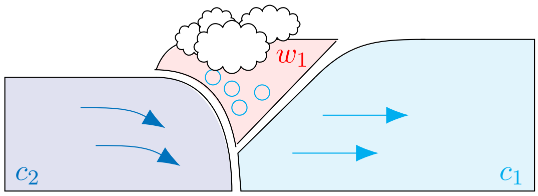

Figure 7: Cold occlusion: The cool air pushes underneath both other fronts. An occluded front is created, bringing heavy precipitation.

However, if the succeeding cold front is carrying cooler air than the preceding cold front, the occlusion is called *warm occlusion* [5].

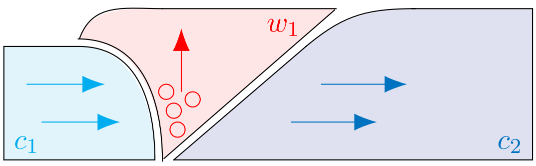

Figure 8: Warm occlusion: A cold front catches up with a warm front preceded by cool air, forcing the warmer air inbetween to go up, creating a thermal.

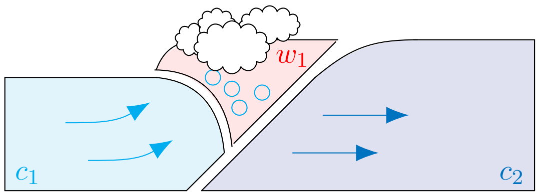

Figure 9: Warm occlusion: The cold front is forced to climb over the cool air, pushing the warm front up. An occluded front is created, bringing heavy precipitation.

2.3 Classifications

In order to create a weather rendering system that is able to display many different cloudscapes, all types of clouds have to be understood first. The World Meteorological Organization (WMO) describes ten distinct cloud classifications. For each of those, there are further subtypes. For simplicity, those subtypes will be disregarded in this project.

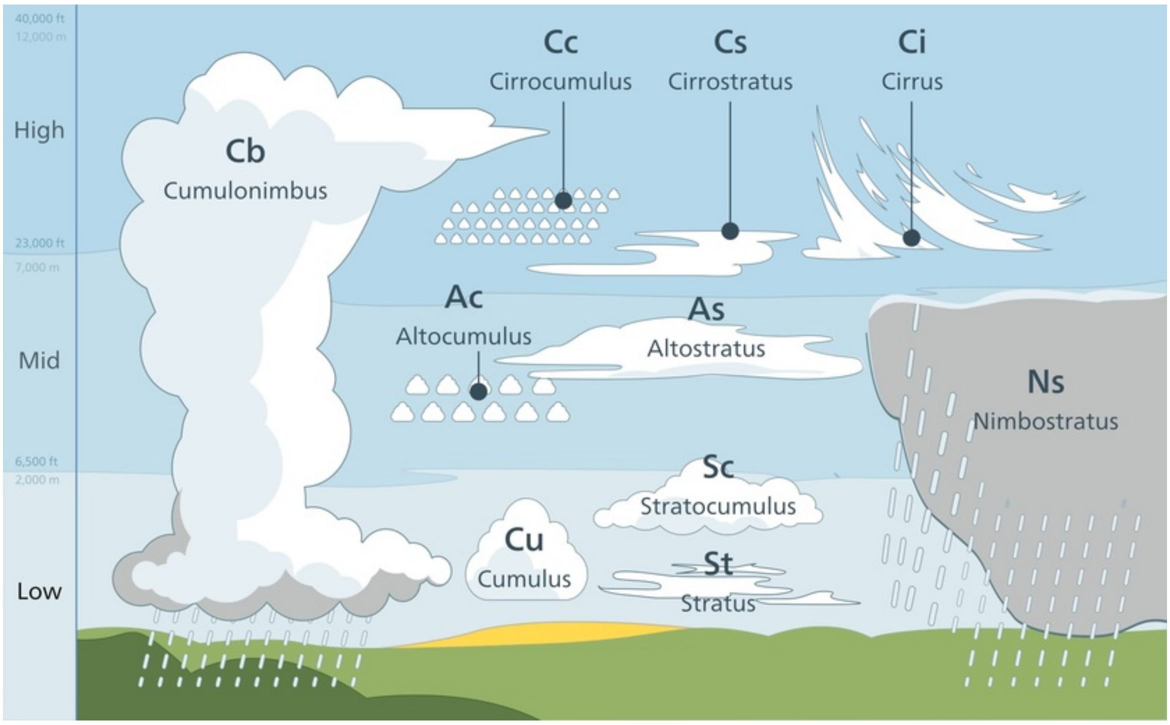

Figure 10: Distinct classifications of cloudshapes in the troposphere [6].

This graphic above provides and excellent overview of all distinct cloud types. Each type is depicted in its signature shape and marked with the scientific name and abbreviation. Natural clouds are typically identified by two major factors: shape and altitude. The altitude, which is the distance from sea level to the cloud, is further split into three categories "low", "mid" and "high". This corresponds to the altitude at which the cloud usually forms, up to twelve kilometers above ground.

All of those clouds are formed in the troposphere, Earth's lowest atmospheric layer. Certain clouds may occur in the stratospheric or even the mesospheric layer, but they are usually a rare sight. Therefore, those clouds will not be covered in this project.

2.3.1 Cirrus

Cirrus clouds consist of thin, hair-like strands. They fall into the "high" altitude group and mostly appear in a bright white color, although they may take on the colors of the sunset or sunrise. Typically, they are formed when water vapor undergoes desublimation, the process in which gas turns into solid. This occurs when the water vapor freezes rapidly at high altitudes, turning into ice crystals.
However, cirrus clouds can also form from air that flows outwards of thunderstorms.

Figure 11: Cirrus clouds [7].

Interpretation: Fair weather, but they might announce the arrival of warm front in 12-24 hours, which is often preceded by rain several hours in advance. Even though cirrus clouds indicate precipitation, they themselves do not produce rainfall [8].

2.3.2 Cirrostratus

Cirrostratus clouds are similar to the cirrus clouds, only that they are even thinner. Those clouds depict more of a veil than a single cloud shape. They form under the same conditions as the cirrus clouds and can cover a massive area of the sky, spanning thousands of kilometers.
Cirrostratus clouds sometimes produce white rings or arcs of lights around the sun or the moon called the *halo phenomenon*. Sometimes, the cirrostratus clouds are so thin that the halo is the only way to tell if there are cirrostratus clouds.

Figure 12: Cirrostratus clouds [9].

Interpretation: Fair weather, but they indicate a warm front within one or two days, bringing precipitation [10].

2.3.3 Cirrocumulus

Similar to the other clouds of the cirrus-family, the cirrocumulus are composed of ice crystals and formed at high altitudes. They are made up of many small, white, puffy clouds called *cloudlet*s. Their wooly look give the cloud the name *cumulus*.
Cirrocumulus clouds are realtively rare, as they are naturally only formed when a turbulent vertical current meets a cirrus cloud layer. The cirrus cloud then disperses into many cloudlets.

Figure 13: Cirrocumulus clouds [11].

Interpretation: They do produce precipitation, but it never reaches the surface, meaning that cirrocumulus clouds are typically associated with fair weather [10].

2.3.4 Altostratus

The name for this grey, uniform sheet of clouds consists of the latin words *alto* (height) and *stratus* (layered), summing up their appearance accurately. Altostratus clouds usually cover the whole sky and form a dull blanket of monocolored clouds with very few features. The sun- or moonlight may shine through them, but will most likely not be strong enough to cast defined shadows.

Figure 14: Altostratus clouds [10].

Interpretation: Altostratus clouds usually indicate precipitation, even more so if they are are preceded by cirrus clouds. If the precipitation increases in persistence and intensity, the altostratus clouds will lower and thicken into nimbostratus clouds.

2.3.5 Altocumulus

As with the cirrocumulus clouds, altocumulus clouds consist of small, puffy, white and grey cloudlets. These cloudlets are usually slightly bigger than the ones of the cirrocumulus cloud. It is easy to tell them apart, as the altocumulus cloudlets are usually more grey than white and are shaded on one side. Altocumulus clouds can form through the dispersion of altostratus clouds or through convection (see subsection 2.1).

Figure 15: Altocumulus clouds [12].

Interpretation: Usually, they are found in settled weather. They do not produce precipitation that reaches the surface.

2.3.6 Nimbostratus

The nimbostratus clouds are the vast, grey clouds that bring heavy rain or snow for a longer period of time, sometimes up to multiple days. With their dark and gloomy appearance, they convey a dreary mood along with the persistent precipitation.
The thick, featureless layers of cloud are often formed by occluded fronts, when an altostratus starts lowering and gets denser [13].

Figure 16: Nimbostratus clouds [10].

Interpretation: They bring long-term rain or snow for several hours or days.

2.3.7 Stratus

Stratus clouds are low-layer clouds that usually only form in calm, stable conditions. They are often described as "high fog" as the have similiarities in appearance.
Stratus cloud are formed by cool, moist air that is raised by mild wind breezes.

Interpretation: They indicate quiet weather conditions, but sometimes produce sprinklings of rain.

Figure 17: Stratus clouds [10].

2.3.8 Cumulus

Probably the most picturesque type of cloud is the cumulus. Its cotton-like look along with the soft, white color make it appear like candy in the sky.
The individual heaps of cumulus clouds remain strictly separated. The edge of each cloud is fuzzy and may change constantly.
Cumulus clouds are almost exclusively formed by convection. This is why they are a good indicator for gliders and pilots that there are upward winds [10].

Figure 18: Cumulus clouds [10].

Interpretation: They indicate fair weather, but can develop into cumulonimbus clouds, if weather conditions allow it.

2.3.9 Stratocumulus

These low-layer patches of cloud consist mainly of water droplets, absorbing a lot of light, giving them a saturated grey color.
They are the most common clouds on Earth and usually form when there is a change in weather or when a layer of stratus cloud breaks up. This means that stratocumulus clouds are present near cold, warm or occluded fronts.
Stratocumulus do not produce precipitation themselves, but are formed in many different conditions, including rainy or calm weather.

Figure 19: Stratocumulus clouds [10].

Interpretation: They announce an instability of the atmosphere and are usually present before an occlusion of weather fronts.

2.3.10 Cumulonimbus

Cumulonimbus clouds are massive, high-towering heaps of cloud, spanning over the whole troposphere. Their top is often shaped like an anvil, whereas the base if flat and dark, giving them a menacing look.
They are referred to as thunderclouds, because they are the only type of cloud that is able to produce hail, thunder and lighting [15].
Cumulonimbus clouds are formed trough natural convection or as a result of forced forced convection when a cold front pushes up warm air.

Figure 20: Cumulonimbus clouds [14].

Interpretation: They cause extreme weather like heavy torrential rain, hail storms, lighting and even tornados.

3 Implementation Approach

Clouds are comprehensible indicators for telling the weather. They offer many visible features to make an rough prediction of the weather conditions, or weather changes to come. As described in subsection 2.3, some cloud types only form under specific conditions. Also, whenever certain clouds are present, precipitation is shortly followed, as it is with altostratus clouds.
Those factors allow a prediction of the weather, but for this project, the process is reversed. The given data is not an image of clouds, but meteorological measurement data, and the desired outcome is not a prediction, but an image of clouds.

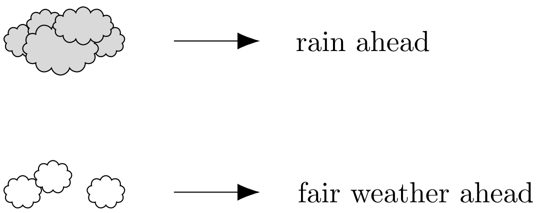

Figure 21: Weather information based on visual data.

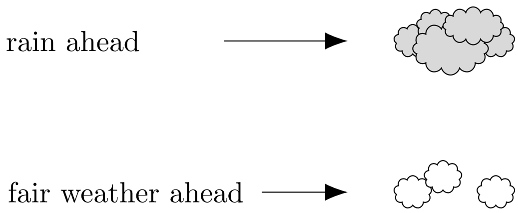

Figure 22: Visual construction based on weather information.

For any given day to render, an implementation would require data from that day but also from the near future of that day. So, in order to render a cloud image for day x, a potential algorithm could look like this. Note that the listing below describes only an idea and is by no means final or compulsory.

```
// weather data including 7-day forecast
WeatherData data;

function renderClouds(Day x) {
    if (x > TODAY + 7) throw;

    d1 = data.getDataFor(x);
    d2 = data.getDataFor(x + 1);
    d3 = data.getDataFor(x + 2);
    // and so on...

    // sophisticated checks about current and future state:
    if (d1.isRainy)
        return renderer.cloudsOnRainyDay();
    if (d2.isRainy)
        return renderer.cloudsBeforeRainyDay();
    if (d2.isRainy)
        return renderer.clouds2DaysBeforeRainyDay();
    // and so on...

}
```

Listing 1: Pseudo-code of cloud render algorithm

3.1 Look-Ahead Issue

The approach as described above relies on having data from a couple of days ahead of time. Assumed that number of days is t, then the weather data for day x could only be rendered t days after x. That would mean, for such an approach to work, the weather of today can not be rendered before t days later.
In this case however, the weather measurement data retrieved from *meteoblue* also contains a seven-day weather forecast. Given that t is less than or equal to seven and an implementation still produces accurate cloud imagery, it would no longer be an issue.

Glossary

Altitude A vertical distance measurement, in this context specifically the distance from sea level to the given object. 2, 5, 6

Cloudlet Small, white, puffy clouds that come in large quantities, together forming a cloud of the cumulus family. 6, 7

Cold front A cold weather front, the boundary of a mass of air that carries cold or cool air. When colliding with a warm front, precipitation is often followed.. 3, 4, 9, 13, 15

Convection The process of warm air rising from the surface and cooling at higher altitude, of which the moisture is then condensed into clouds. 2, 7, 8, 9

Desublimation The process of gas transitioning to liquid without passing through the liquid phase. 6

Fractal Brownian motion Different iterations of continuously more detailed noise layered on top of each other. i

Halo phenomenon White or colored rings or arcs of light around the sun or the moon, produced by cirrostratus clouds. 6

Noise A randomly generated pattern, referring to procedural pattern generation. i

Occluded front When a cold front overtakes a warm front, it pushes the warm air upwards (thermals). The moisture of the warm air condenses as it rises, creating water vapor. This often results in clouds with precipitation. 4, 7, 8, 12, 15

Occlusion In meteorology, the clash of a warm front and a cold front. See occluded front.. 4, 15

Precipitation Rainfall. The result of atmospheric water vapor that has been condensed and now falls from clouds. 3, 4, 6, 7, 8, 10, 12, 13, 15

Procedural Created solely with algorithms and independant of any prerequisites. i, 12

Ray marching Ray marching is a type of method to approximate the surface distance of a volumetric object, where a ray is cast into the volume and stepped forward until the surface is reached. i

Surface normal A *surface normal* or *normal* is a vector which is perpendicular to a given geometry, like a triangle or polygon. i

Thermal In relation with meteorology, the hot, rising air from convection is called "thermal". 2, 3, 4, 12, 15

Volumetric This describes a technique which takes a 3D volume of data and projects it to 2D. It is mostly used for transparent effects stored as a 3D image. i

Warm front A warm weather front, the boundary of a mass of air that carries mild or warm air. When colliding with a cold front, precipitation is often followed.. 3, 4, 6, 12, 15

Water vapor Evaporated water in a gaseous form. 6, 12

Weather rendering system The Unity application that is implemented during this project. It takes in live data from a weather service and uses topological elevation models to create a weather simulation, which is then rendered and up for comparison with live photographs. 5

Weather front A boundary between to air masses, which differ in temperature, wind direction and humidity.. 2, 12, 13

WMO A specialized agency conducting atmospheric science, climatology, hydrology and geophysics. 5

References

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