Qualitative Simulation of Cloud Formation and Evolution

Fabrice Neyret

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Fabrice Neyret

DGP - University of Toronto
SF 4306-C, 10 Kings College Road
Toronto, Ontario, M5S 3G4, Canada
Fabrice.Neyret@inria.fr http://www.dgp.toronto.edu/people/neyret

Abstract.

Cloud simulation models are rare in computer graphics, although many rendering algorithms have been developed to evaluate the illumination and the color of gaseous phenomena. The laws of fluid mechanics used for physical simulation require a fine resolution in space and time, and solving the Navier-Stokes equation in 3D is in general quite costly. However, many heuristics, dealing with various scales, can be used to describe the evolution of the shape of convective clouds such as cumulus. These go beyond the classical equations governing the motion of each element of fluid volume. Physicists characterize the identity and behavior of phenomena such as bubbles, jets, instabilities, waves, convective cells, and vortices. Moreover, the shape of a convective cloud can be considered as a surface, so that we only require detailed information near the periphery of the cloud volume.

A guiding principle in our ongoing research is to take advantage of this type of high level knowledge available at various scales in order to obtain a simulation of convective clouds that may not be physically-accurate, but that will be perceptually convincing.

Keywords: clouds, simulation, natural phenomena

1 Introduction

Atmospheric convective phenomena such as cumulus clouds and billowing smoke are important natural phenomena that often occur in outdoor scenes. However, few animated clouds or smoke generators are available for computer graphics. The evolving fractal shapes of clouds are difficult to model, because what we see is the large scale result of complex non linear physical phenomena, combining the effects of fluid mechanics and thermodynamics. Moreover the numerical values of some of the real parameters required in numerical models (e.g. turbulent viscosity) are not readily known. Real boundary conditions such as heat and moisture generation on the floor are also not well understood. Furthermore, the Eulerian schemes used to solve the equations require a grid having at least the resolution of the smallest detail we wish to see, while the volume of the desired scene may be quite large. Thus, a physical cloud simulation using local equations is a task that is especially consuming in terms of memory and time !

By using a macroscopic approach, atmospheric physicists have characterized many specific structures appearing in fluid phenomena, whose evolution, properties, and interactions can be measured. Some of these structures are as follows (some are shown in Figure 1):

- *Rayleigh-Taylor instability*: when a dense (cold) fluid layer lies on a light (hot) one, bulbs appear at the interface, rising to become 'atomic mushrooms', then becoming *bubbles* once they take off.
- *bubbles*: their ascending velocity, rate of expansion, and cooling through mixing can all be estimated.
- *jets* or *columns*: bubbles often 'drip up' along a vertical chimney. When a train of decelerating bubbles collides, the bubbles merge in a column having more intense behavior because the mixing with background air is less important.
- Once a bubble reaches the dew point, the water vapor it contains starts condensing and makes the rising bubble visible. The release of latent heat of condensation boosts the rising motion, and is the driving force for cumulus phenomena.
- Without mixing, a bubble's temperature decreases by 10 degrees per kilometer until reaching the dew point altitude, and then becomes 6 degrees per kilometer. This is different than the ambient air temperature, whose usual vertical thermal profile decreases by 6.4 degrees per kilometer. Near the floor, this variation is logarithmic, positive in summer and negative in winter. Convective motions can thus only start around summer.
- *Turrets*: bubbles are also born and rise on the top and from the sides of clouds, for the same reasons as near the floor, i.e. difference of density between two layers. The balance of forces tend to make them move in a direction that is halfway between the vertical and the cloud surface normal [14] (see Figure 4).
- *Kelvin-Helmholtz instability*: on the boundary of fluids having different velocities (e.g. a bubble top surface, see D on Figure 2), *waves* appear.
- These waves amplify and turn into *vortices*.
- On the top of a rising bubble (e.g. on a cloud surface), the balance between the mixing and the shearing in the surface layer produces waves with a characteristic size [5, 6] (about 1/10 of the bubble radius).
- *Vortices* tend to break into smaller vortices, up to the quasi-molecular size where the energy can be dissipated as heat. This transfer of energy among vortices of different scales is known as *Kolmogorov cascade*, and its power spectrum can be estimated.
- *Benard cells*: inside a fluid layer with a hot bottom surface and a cold top surface having a Rayleigh number in the correct range, regular convective cells appear. These usually are hexagonal in shape, with the fluid rising at the middle and sinking at the borders.
- Under specific wind conditions, the cells turn into ribbons, orthogonal or parallel to the wind direction depending of the wind velocity.

A classical survey about atmospheric structures can be found in [15]. More about convective clouds is explained in [8]. Advanced topics about plumes and thermals are presented in [1]. Interesting information concerning air motion below and around natural clouds can also be obtained from experienced paragliders [11].

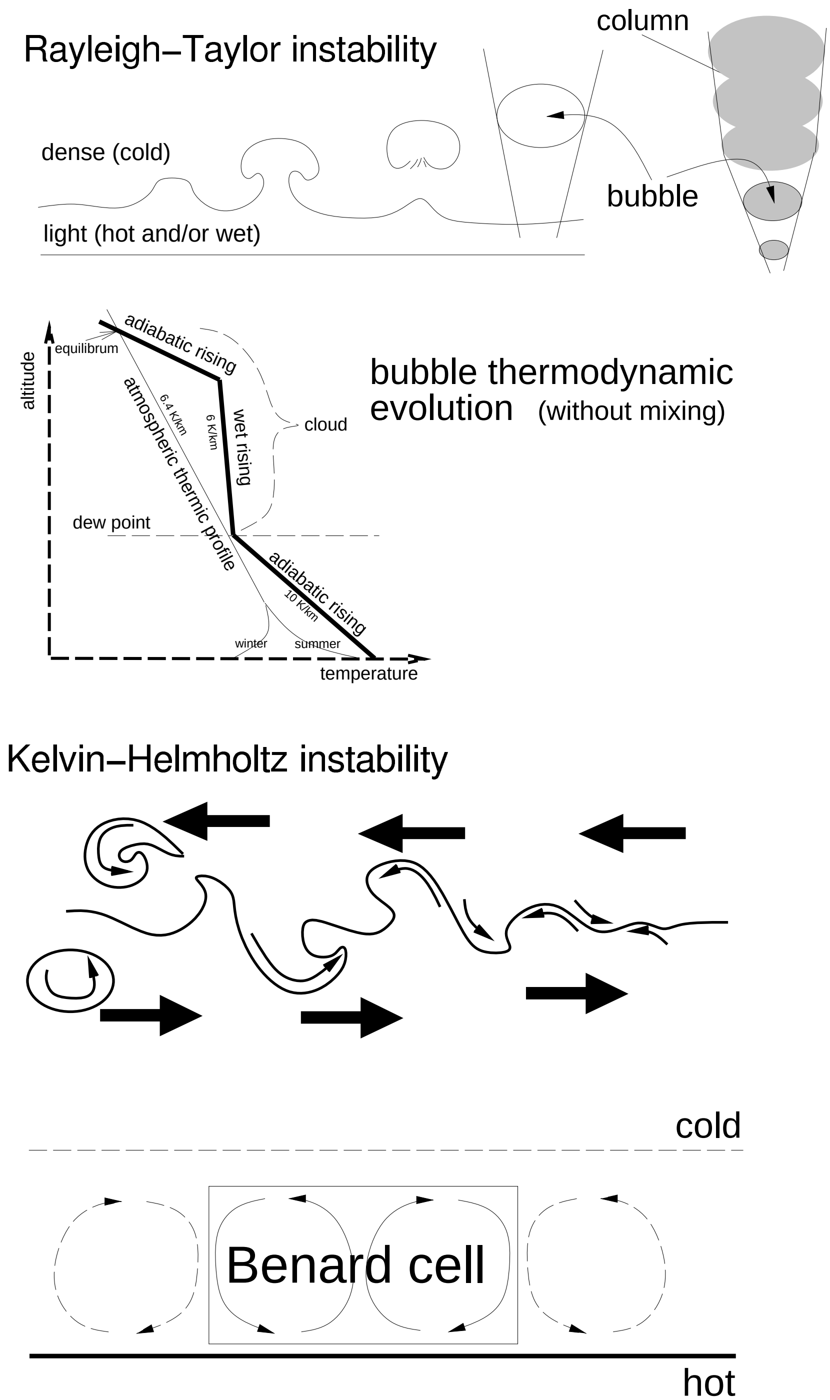

Figure 1: Some macroscopic structures in fluid motions.

We aim to incorporate most of this knowledge in a computer graphics model. In this paper, we take into account 3 phenomena at various scales (see Figure 2):

- hot spot generation on the ground, from which the bubbles rise (see section 3.1). We also hope to have the Benard circulation simulated at this stage.
- we used to simulate bubble rising and dew point reaching. However this model is too complicated (i.e. it contains too many equations), and probably useless. We don't describe it in this paper, rather assuming that the dew point altitude is known and constant, so that the travel between the floor and the cloud bottom doesn't needs to be simulated.
- bubble creation and evolution inside the cloud, and emerging as turrets on the top and the border (see section 3.2).
- waves and vortices convected at the surface of the turrets (see section 3.3).

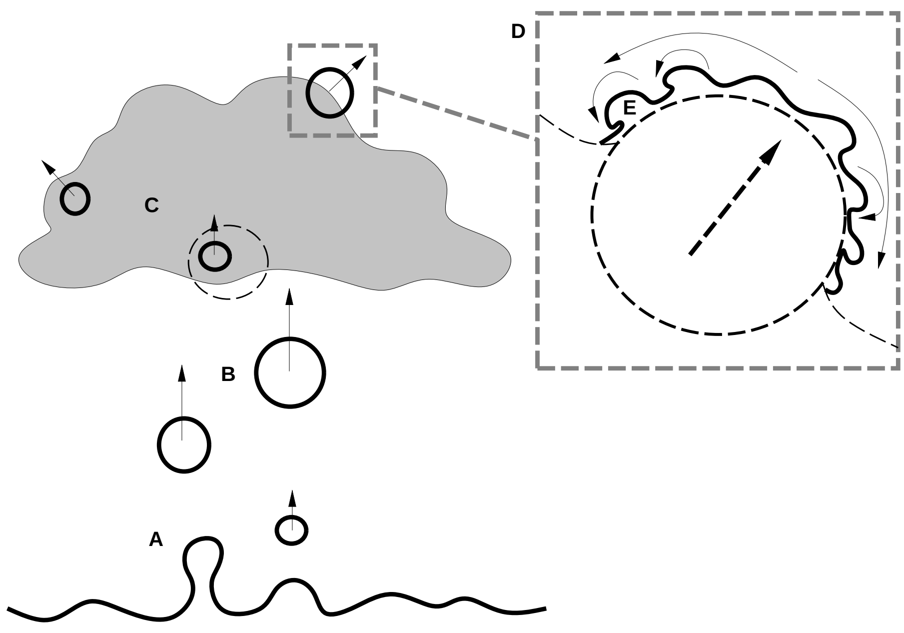

Figure 2: Our general scheme: bubbles birth (A) and rising (B), cloud bubbles motion (C), bubble substructures (D), waves becoming vortices (E).

2 Previous Work

Many physical simulation techniques exist, most of which are not used to produce images. Few physicists are really interested by the shape of the clouds. Instead, they are interested by the heat field, the velocity field, and the formation of rain drops. Simplifications are commonly assumed for efficiency, e.g. 2D vertical simulation, axi-symmetric simulation. In our work we are not interested by such costly simulations which are not particularly tuned for providing a shape.

In 1984, Kajiya proposed a model to achieve some clouds simulation [9]. These equations are very close to the physical models, so that the affordable resolution is very low (10x10x20).

Two papers simulate fluids in the context of computer graphics, and with an appropriately-high resolution [2, 10]. However, these deal only with the 2D case. Alas, not only there is a cost gap between 2D and 3D, but 2D and 3D fluids motions are qualitatively different in nature.

Several computer graphics models exist to produce cloud shapes using various kinds of procedural noise, possibly generating an explicit volumetric density field. Some fractal models exist as well. However, none of these models deal with the growth and animation of the cloud, which is the main goal of our work. We would like to consider that the shape is the consequence of the movment.

In [3, 4], Garner proposes an interesting primitive, the textured ellipsoid, covered with a procedural noise opacity which fades on the horizon of the shape so that one cannot see the elliptical border. In the 1985 paper, he describes how this ellipsoid can rise from the soil and grow, then becomes visible and stabilizes at a given altitude. While the images are detailed and interesting, the animation on the ellipsoid surface is simply obtained using an offset for the Perlin noise, which doesn't correspond to any real convection effect.

In [12, 13], Stam uses white noise filtering to generate a wind field with a mass conservation property and having defined statistical properties. Smoke, flames and cloud shapes are achieved by combining spheres warped by the wind field. The wind model provides for very fluids-like motions, but cannot generates real vortices, because these cannot be described by the second order statistical moments of the fluid velocity.

A new approach is thus required !

3 The proposed model

3.1 Bubble generation

In summer, the sun intensely radiates the surface of the earth. Depending of the type of soil (earth, water, concrete), orientation and vegetation (barren, grass fields, forest), the ground heats the bottom layer of air and provides moisture[1], so that the bottom layer becomes lighter than the neighboring air layers above. At the hottest points above the floor, the air begins to rise, and in doing so, sucks the hot air from the surrounding terrain. Depending on the conditions, this will lead to a single bubble, a train of bubbles, or even a column formation.

We simulate the bottom layer of air as a set of hot air parcels trapped on the ground, modeled as 2D particles. The ground heating due to the sun is modeled by creating new hot air parcels at random. One may use a texture indicating the kind of soil, thus controlling how much energy the ground releases at each point. The rising is due to the difference in air density ρ relative to the upper air layer, which occurs because of the difference in temperature. The buoyancy force per unit mass is $g(T-T^*)/T^*$, where T is the parcel temperature and T^* is the background temperature. However, the buoyancy force is opposed by friction, and the temperature stratification near the ground makes it difficult to define a 'background temperature'. We assume that the rising force is proportional to the heat gained $E=(T-T^*)$ provided by the sun, with an ascendancy coefficient to control the rising ability: the rising force is $f_r(i) = c_{asc}.m(i).E(i)$ for the air parcel i.

We also compute the attraction force created between the parcels by the vacuum effect of the displaced (rising) air. We assume a $1/d^2$ decrease law for this attraction: $f_a(P) = \sum_i \frac{P(i)-P}{\|P(i)-P\|^3}.f_r(i)$. A $1/d$ law would tend to favor a single hot spot attracting all hot air parcels. We also consider a viscosity coefficient to control the stability of the air flux along the surface. From these terms we compute the 2D air transport toward the hot spots. Parcels closer than a given distance are merged. When the rising force exceeds a threshold, which will occur at the hot spots, we consider that a bubble is born, to be given to the model managing the bubble transportation in air. The corresponding mass is subtracted from the remaining parcel of ground air.

The fact that the surrounding air is displaced towards a hot spot supposes that fresh air comes from above, which will decrease the chance for this same location to heat further, thus stabilizing the air transport (main hot spots tend to stay at the same place). We expect that this may emulate Benard cell behavior, but more studies should be done with respect to the resulting distribution of hot spots as a function of the value of the ascendancy and viscosity coefficients, and of the attraction law.

[1] Moist air is lighter than dry air, due to the molecular masses of H_2O and air (80% N_2, 20% O_2). Air density is also inversely proportional to temperature. We can merge the two parameters in one, the *virtual temperature*. Typically, 3% of vapor is roughly equivalent to 3 degrees of heat. Thus, in this whole section, T is the virtual temperature.

3.2 Cloud evolution

As explained in the introduction, we do not model within the scope on this paper the bubble rising from the ground to the dew point altitude. The bubble becomes visible at the dew point altitude because of condensation, thus marking the boundary forming the floor of the clouds. We assume that the bubble generated at the previous stage appears directly at the dew point altitude, above the initial point of formation. One may add some bias in order to take into account horizontal displacements attributable to wind.

Because of the quantitative changes in the mixing phenomenon and of the dynamics of the motion below and above the dew point altitude (the air is more hot, wet and turbulent inside the cloud), one cannot assume that a same well-defined bubble being born on the ground will rise up to the top of a cloud. The matter is redistributed. We consider a model where the cloud is fed from the earth's surface with bubbles, and where new bubbles are created inside the cloud depending on the local conditions[2].

In our model, the inside of the cloud is composed of static bubbles. The volumetric resolution is thus crudely represented, with sufficient accuracy for air transport to occur. We use *potential temperatures*, i.e. the temperature that an air parcel would have if it was at the sea level, rather than the real temperature, the latter being affected by the pressure decrease with altitude.

The birth of a bubble inside or at the border of a cloud is due to a local temperature gradient (causing a Rayleigh-Taylor instability). Our computational model works as follows. We first look for the hottest neighborhood, assuming that the motion is due to newly arriving matter, and to accumulation of hot matter. We then compute the barycenter of this neighborhood using temperatures as weights, where the new bubble will be born. The new bubble takes the heat of each bubble in the neighborhood, according to a factor decreasing with the distance d, namely $\frac{1}{1+d/D_{\frac{1}{2}}}$, and in a proportion controlled by a global coefficient τ_{conv} (between 0 and 1). $D_{\frac{1}{2}}$ is a coefficient corresponding to the distance contributing at 50%. We chose it to be equal to the bubble radius so that the bubble recomposition is quite local.

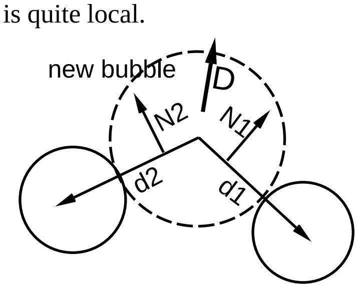

Figure 3: New bubble inside a cloud.

The direction of the bubble displacement depends on the local heat gradient, which is estimated by summing the normals $\vec{N_i}$ (taken in a vertical plane) to each bubble direction $\vec{d_i}$ from which the new bubble is taking heat: $\vec{N_i} = \vec{d_i} \times \vec{horiz}$, $\vec{D} = \frac{1}{nb} \cdot \sum_1^{nb} (\vec{N_i}/||\vec{N_i}||)$, see Figure 3. Note that in a homogeneous temperature field,

[2] Some heuristico-physical models even consider 3 stages between the floor and the clouds, where the bubbles are rearranged, so that the bubbles reaching the cloud are not the same as the ones that left the floor. These models focus on heat and moisture exchange between successive layers.

the direction is null (no instability), while at the boundary of such a field, the direction follows the boundary normal. Beyond this local potential temperature gradient, there is a vertical gradient of real temperature due to the pressure gradient. This has no effect however, as it is directly counterbalanced by gravity. The density gradient is due to the pressure, which results from hydrostatic equilibrium: $\frac{\partial P}{\partial z} = -\rho.g$. We do need to add the important effect of latent heat released by condensation as long as a wet air parcel rises, as illustrated in Figure 4. This acts as a motor in the cumulus growing. For typical physical values, this is equivalent to adding a unit vertical vector to the computed direction, thus verifying the observation that turrets in natural clouds grow in a direction that is the halfway between the cloud normal and the vertical [14].

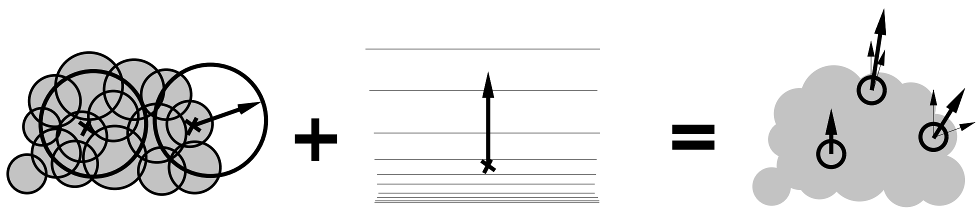

Figure 4: The combination of the potential temperature gradient and the latent heat release controls the bubbles motion inside the cloud, and the turrets formation on the border.

Once the bubble has moved a given distance in its chosen direction, one of several things can occur (see Figure 5):

- if the bubble is in a sparse area, we keep it in order to be used in further air transportation. It marks the occupation of this location by cloud matter.
- if the bubble appears on the top of the cloud, we keep it because it is visible. If this hides a neighbor, we can delete the neighbor.
- otherwise we can destroy it and distribute its mass and heat to its new neighbors.

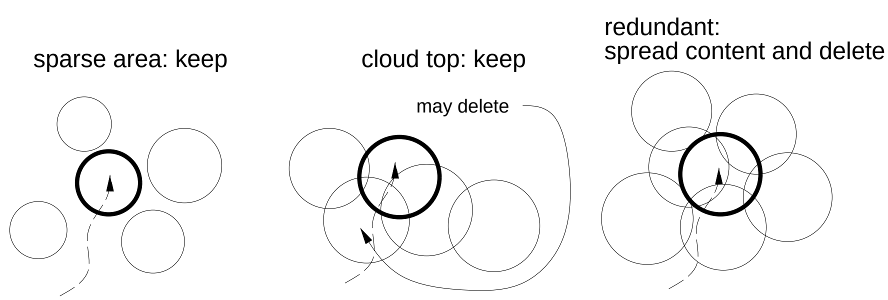

Figure 5: Destiny of the bubble after its move.

In Figure 6 we show the time evolution of the external envelope of bubbles, as visualized by placing a point at the center of each main vortex on a bubble surface. The purpose and use of vortices is described more thoroughly in the next subsection.

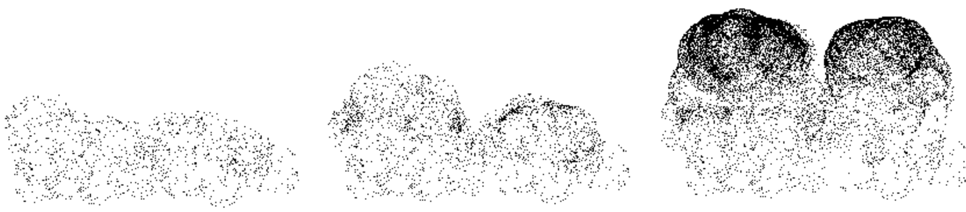

Figure 6: Growing 3D cumulus cloud.

3.3 Small scale shape

The surface of the cloud is materialized by structures smaller than the bubbles themselves, i.e. *waves* that become *main vortices* (see D on Figure 2), and subvortices. We assume a recursive structure, as illustrated in Figure 7. A bubble is considered as a sphere, onto which are convected the main vortices, which were initially waves having about 1/10 of the sphere radius [5, 6]. These vortices are also considered to be spherical, and subvortices are themselves advected upon their parent vortex surface in a recursive fashion.

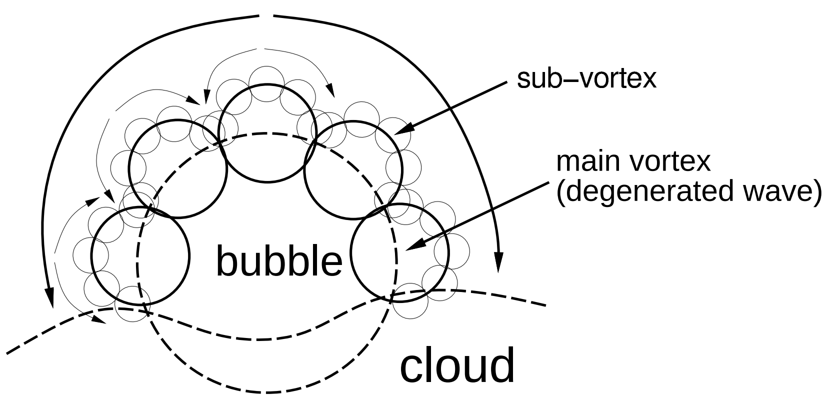

Figure 7: Bubble substructures: main vortices and sub-vortices, each being advected on its parent surface.

In our model, when a bubble reaches and crosses the cloud's top surface, it pushes back this surface, thus 'stealing' the matter (i.e. substructures) from the bubbles residing in the occupied place. These substructures are thus detached from their bubbles and re-attached to the rising one, and advected on its surface as shown in Figure 8. New matter (i.e. waves) appears on the top (in bold in the figure).

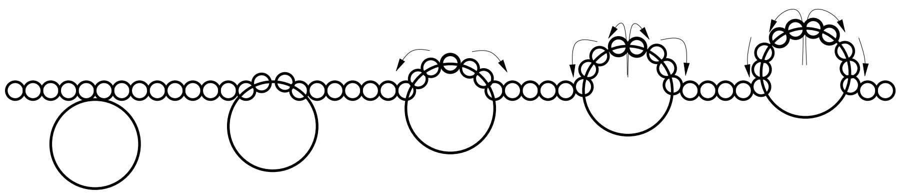

Figure 8: Matter advection.

The matter that appears on the top is advected to the sides where it is then stationary with respect to the background, while the bubble is rising. The rotation around the bubble compensates for the bubble rising, so that the advection acts much like a vertical tank track. If a single bubble rises as a turret, the matter is dropped when it reaches the largest location of the bubble, thus forming a cylindrical column. This is shown in Figure 9.

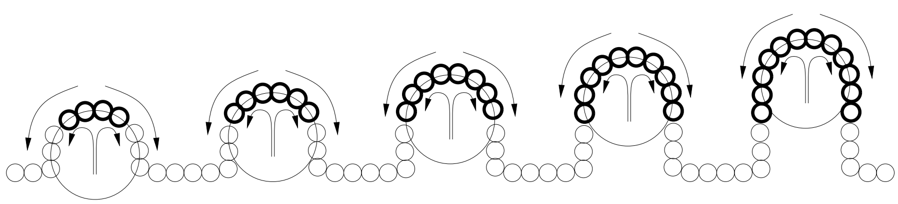

Figure 9: Turret formation.

This structure is also suitable for the representation of billowing smoke, where each individual bubble remains visible as it rises, because the dust replaces the water, and because the smoke column is thin and sparse oppositely to a chubby cumulus. For billowing smoke, the motions are more violent in the vortices at the surface of the bubble, and we consider the vorticity acquired by the small structures, that makes them roll. This remains the subject of future work, however.

In Figure 10, we show an OpenGL rendering of a single bubble with its substructures. These are frames taken from two animations of a single smoke bubble. Shadows on the left image are computed using a shadowmap. The spheres on the right image are textured.

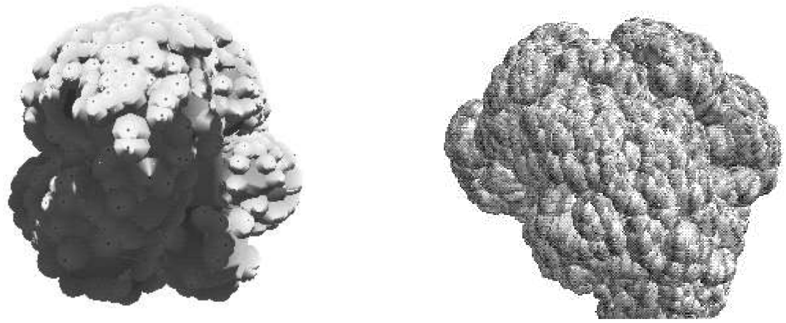

Figure 10: Two bubbles and their substructures rolling on their surfaces.

4 Conclusion

The ongoing work we have presented in this paper proposes to qualitatively simulate the growth and animation of convective clouds. This is achieved by simulating and combining atmospheric structures of various scales. Bubbles are the largest scale structure we use and are responsible for displacements of 3D air parcels in our model. We combine several models to deal with bubbles birth near the ground, bubbles rising up to a cloud, and bubbles moving inside a cloud. Smaller scales are used to add visual complexity for motion and shape on the cloud surface. The smaller-scale substructures are attached to each bubble lying on the cloud periphery, and themselves have substructures. A substructure is advected on the surface of its parent substructure. The largest level of substructure corresponds to waves on a bubble surface that degenerate into main vortices, while finer substructures correspond to the breaking of these vortices into smaller vortices. The general scheme is illustrated in Figure 2.

Our model and implementation are still at an early stage. The various scales have been implemented individually; we have yet to combine them in a single simulation. The following issues also need to be addressed. There are no special provisions for the initial birth and death of a cloud, while the assumption that a cloud is a surface at these instants is not very realistic. The Benard cell structure is not specifically encoded, so there is no guarantee that clouds stay distant from each other. The bubble motion inside the cloud is effected one bubble at a time, while several bubble motion events should be treated simultaneously. Lastly, we have specified the animation of the cloud, but we do not specifically deal with the rendering. The simplest approach to rendering consists of drawing the smaller spherical substructures, possibly with textures. The addition of a global 'skin' upon these structures may also improve the visual aspect of the cloud surface.

Two extensions arise at this point. It would be interesting to deal with larger scale cloud structures, in order to simulate the shape and the evolution of the sky in outdoor scenes. Another issue is that most of the model can also apply to billowing smoke, where the dynamics of advection is more intense, and were substructures play a more important role.

[3]**Acknowledgments**

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