Parallel Simulation of Barchan Sand Dune Morphology

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This project will implement and develop reduced models of barchan-type aeolian sand dune dynamics, using simplified CFD and sand particle physics. Barchan sand dunes (See Fig 1, Kroy, et al) are currently the best understood type of sand dune, known for high mobility; up to 100 meters in a single year (Bagnold). Barchans are widespread in Earth deserts and are also a common dune on Mars, where they assume a surprisingly large diversity of shapes.

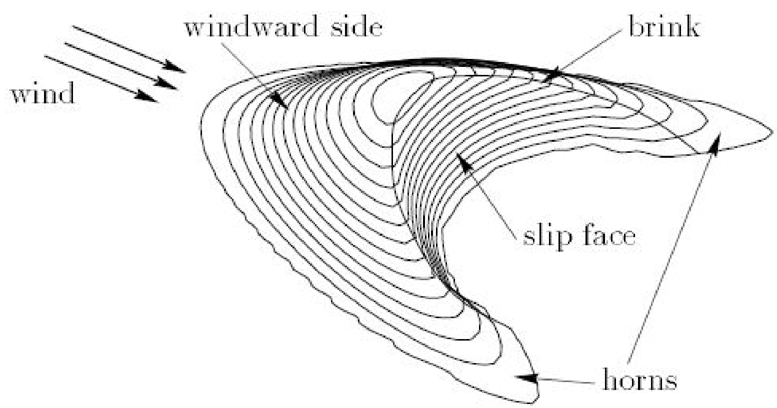


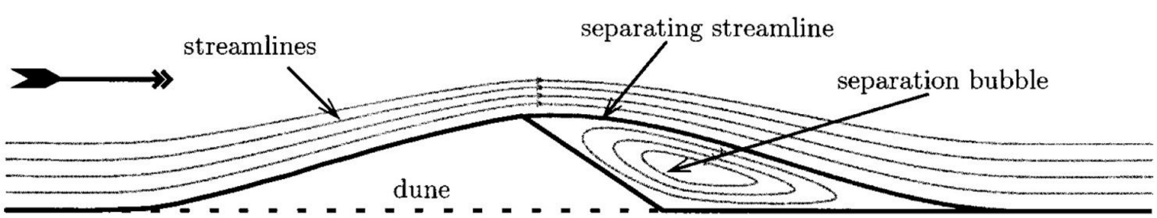
FIG. 1: Sketch of a barchan dune. Sand is eroded by the wind on the upwind or "stoss" side and transported to the brink. Strong deposition occurs due to flow separation behind the brink. On the downwind or "lee" side, sand slides down at the angle of repose (about $32° - 35°$) over a concave slip face.

Dune dynamics can help unearth planetary climate history through inference from older, fossilized dunes (Kok). It can help us understand prevailing wind patterns on other planets. For example, the linear dunes found on Titan are extremely similar to those found in Namibia and suggest strong parallels between climate patterns of the two regions (Lancaster). Clearly, understanding the conditions that cause these dunes to form and propagate on Earth will help us draw inferences about the climate on inaccessible planetary bodies. Additionally, dune dynamics are intimately linked with the presence of dust and aerosols in the atmosphere, and significantly affect weather and climate through a wide range of interactions.

We aim to implement a morphodynamic (continuum) modeling approach, which has seen significant improvement in the last two decades in dune modeling (Kroy).
Secondly, we aim to extend the numerical methods already developed and optimize them for a highly parallelized python computing environment, implemented and optimized across multiple, non-homogenous compute nodes, using python packages such as Numba, mpi4py, and Dask.

This will greatly help in scaling this method to larger simulations, exploring the interplay between wind direction and dune morphology over larger areas..
Finally, we plan to integrate a concise and intuitive set of visualization tools, allowing the user of the code to get a clear view of how each process contributes to dune dynamics.

Key quantities that we will simulate are: horizontal surface velocity v(x,t), over a sand height profile h(x,t) at all positions x and times t, and a sand flux q(x,t). An artificially smooth surface h(x,t) is used to generate (without solving the full CFD) a surface shear stress perturbation above the sand profile h(x,y). This works well for smooth heaps with gentle slopes, the application to a dune profile with slip faces and sharp brink lines is modeled via a phenomenologically defined separation bubble as shown in the figure below.



On the lee side, inside the separation bubble, a different flow model is used, coupled to sand slip and its effect on sand flow.

Initially, we will develop a simplified 2-D case, this will help us implement the basic methods for the physics of sand transport and fluid flow over non-smooth dune shapes. Next the basic framework of the parallelization tools will be implemented in order to support the increased computational demand of a full 3-D sand dune simulation. Finally, we will study and visualize the effect of wind distributions on barchan dune formation and steady-state geometry.

The project will be hosted on a github repository to help with code version control and debugging. In addition, we will integrate basic unit tests into critical components of the code. Finally the code will be developed in a way that will allow simple test cases to be run, where one might easily be able to determine if the result is wrong from the produced visualizations. For example, running a 2-D case of the center slice of the dune will be an easy way to test if the fluid dynamics solvers integrate properly with the equations determining the surface flow of sand on the dune. We can hopefully compare the results of our model to real-world results, for example, we know that given a steady wind, a barchan dune will continue to move in a straight line and maintain a relatively constant shape.

References

Kroy, Klaus, Gerd Sauermann, and Hans J. Herrmann. "Minimal model for aeolian sand dunes." Physical Review E 66.3 (2002): 031302.

Kok, Jasper F., et al. "The physics of wind-blown sand and dust." Reports on progress in Physics 75.10 (2012): 106901.

Bagnold, R. A. "The physics of blown sand and desert dunes: New York." William Morrow & Company (1941).

Lancaster, Nicholas. "Linear dunes on Titan." Science 312.5774 (2006): 702-703.

Parteli, Eric JR, et al. "Dune formation under bimodal winds." Proceedings of the National Academy of Sciences 106.52 (2009): 22085-22089.