COMPUTATIONAL MODELING OF TERRESTRIAL SUBAQUEOUS AND VENUSIAN NEAR-SURFACE PARTICLE TRAJECTORIES AND TRANSPORT.

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Introduction: The last few decades have seen the growth of numerical modeling as an approach in studying wind-driven dune flow and feature formation processes. Approaches include cellular automaton (CA) models [1], saltation models [2], and Computational Fluid Dynamics (CFD) Models [3, 4, 5, see also [6] for summary]. In this study, we use the CFD approach with a commercial software package to track particle travel distances in terrestrial subaqueous and venusian environments as a function of particle size, density, and wind velocity. The goal of this work is to understand the similarities and differences of particle trajectories within the modeled flow fields for the venusian and terrestrial subaquaeous parameter spaces to facilitate studies comparing feature types found in both flow regimes.

Dune Examples: Both terrestrial seafloor dunes and venusian dunes form in more viscous materials than other planetary environments, and should thus have some similarity in formation processes and potentially morphology.

Venusian Dunes. The only two identified Venusian Dune Fields are Al-Uzza Undae (in Fortuna-Mashenet centered at 67°N, 91°E) and Menat Undae (or Algaonice) which are centered at 25°S, 340°E) and which consist of N-S trending transverse dunes [7, 8]. Venusian dunes measured at Al-Uzza using radarclinometry are reported to be 20-60 m in height, 0.2-0.5 km in width, and 0.5-5 km in length [9]. The Venusian wind speeds are estimated to be ~0.2 - 1.3 m s^{-1} at about 1 m above the surface as recorded by Soviet Venera landers [10]

Terrestrial Seafloor Dunes. Terrestrial seafloor dunes have been observed since the 1960s with side-scanning sonar instruments and limited photography (e.g., [11,12,13]. The seafloor features are smaller than either terrestrial dry land or venusian examples. They exhibit transverse to barchan morphologies, and are typically10-100 m in length, 10s of centimeters to meters in height, with spacings of 10s of meters. The associated seafloor currents are estimated as ~0.3-2 m s^{-1}.

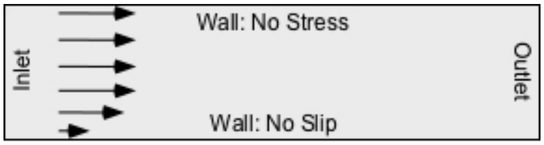


Fig. 1 Computational Boundary Conditions

Computational Approach: For numerical modeling, the computational fluid dynamics (CFD) commercial code COMSOL Multiphysics [14] is employed. This code solves the Navier-Stokes equations using a finite element approach. The flow domain can be solved with either laminar or turbulent approaches (depending on Reynolds number), and the particle tracing module with fluid-particle interactions is used.

Flow Field. The flow field is modeled as a 2-D slice of the near surface, including the boundary layer (see Fig. 1). The computational domain can be scaled to the desired dimensions to accommodate different flow regimes. Steady state conditions for the flow field are assumed, as the primary objective of this study is to examine the steady transport of particle grains in the background fluid flow field. Mesh geometry is physics-controlled, allowing additional resolution at the flow boundary layer. At low velocities and/or high fluid viscosities, the laminar flow module is used, and as progressively higher Reynolds numbers are reached, the turbulent modeling is introduced using a Reynolds-Averaged Navier Stokes (RANS) turbulence model. In most cases, the standard k-ε model is employed and convergence is assumed to be reached when all of the normalized residuals were smaller than 10^{-5}.

Particle Tracing. The model allows the definition, release, and tracking of particles with defined size and density anywhere in the simulation domain. Boundary conditions can be imposed on the walls of the geometry to allow particles to freeze, stick, bounce, disappear, or reflect. Alternatively, a user-defined wall function can be defined, where post collision particle velocity is typically a function of the incoming particle velocity and the wall normal vector. Secondary particles released when an incoming particle strikes a wall can be included. The number of secondary particles and their velocity distribution function can be functions of the primary particle velocity and the wall geometry. For this preliminary study, particles are released at the mesh gridpoints at the domain inlet. If they cross the top boundary (i.e. as part of a turbulent eddy), they are allowed to escape, they can exit the regime entrained within the flow at the outlet, and they are set to either bounce or stick at the flow domain base. As yet, no secondary particles are accounted for (accumulated) at particle-base impact within this study.

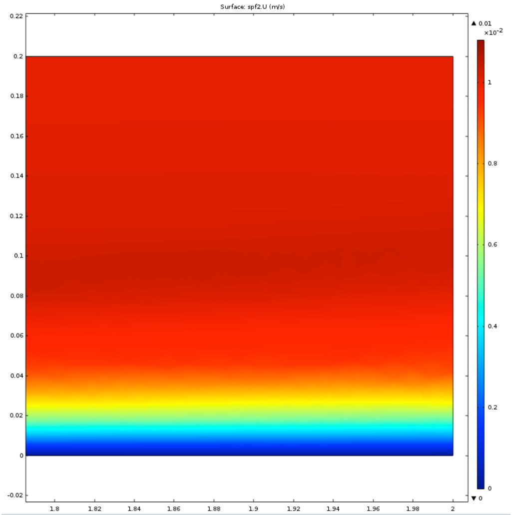
Parameter Ranges. We use the parameter ranges specified in [12] (Table 2) and [15]. While observed dune heights range from approximately 0.5 m to 80 m, this study does not specifically impose them as surface flow obstacles yet. Flow regime domain heights are scaled to at least twice dune height. These can be expanded easily if flow field effects are expected to exceed twice dune height. While this preliminary study does not impose surface obstacles (such as existing dunes) within the flow field, these can be added in future studies. The terrestrial domains are modeled as water and the Venusian approximated as 100% CO_2. The temperature and pressure-dependent parameter range for both water and CO_2 are taken from the default material definitions supplied within COMSOL.

Conclusions: While modeling for this study is ongoing, we find that particle transport for Venusian conditions is most similar to those found on the terrestrial seafloor, among the potential planetary analogues for fluid flow (aeolian or sub-aqueous) depositional environments. The CFD modeling and particle tracing approach can be scaled to yield results as a function of Re number, and particle properties in a series of dimensionless plots. The CFD approach facilitates rapid simulation of the atmospheric or sub-aqueous flow fields using a rigorous approach to particel trajectory modeling, and without making a priori assumptions of boundary layer dimensions or shape.

References: [1] Werner, (1995) Geology 23, 1107-1110. [2] Kokand Renno (2009) JGR 114, D17204 doi:10.1029/2009JD011702. [3] Hermann et al. (2005) Physica A 357(1) 44-49. [4] Jackson D.W.T et al. (2015), *Nat. Commun.* 6:8796 doi: 10.1038/ncomms9796. [5] Faria, R., et al. (2011) Aeolian Research 3, 303-314. [6] Lorenz R. D. and Zimbelman J. R. (2014) *Dune Worlds*, Springer Praxis Books. [7] Greeley et al., (1992) JGR, 97 13319-13345. [8] Weitz et al., (1994) *Icarus*, 112. [9] Lorenz, 4th *Int.Planet.Dunes Wkshp.*, 2015. [10] Keldysh, Icarus, 30, 1977. [11] Lonsdale and Malfait, *Geol. Soc. Am. Bull.,* 85, 1974. [12] Neakrase et al., *Aeol. Res., in review*. [13] Sagan, (1975) *J.Atmos.Sci*, 32. [14] COMSOL Multiphysics® v. 5.2. www.comsol.com. COMSOL AB, Stockholm, Sweden. [15] Neakrase and Klose, (2017), 4th *Int.Planet.Dunes Wkshp.*, 2017 (This volume).

Fig. 2 Examples of laminar (a) and turbulent(b) flow regime velocity fields. The laminar regime shows the boundary layer as a significant fraction of the flow field domain, while the turbulent regime has a much diminished boundary layer.

A. Laminar flow field (water, seafloor conditions). The nominal velocity boundary layer as observed in the velocity field solution comprises roughly 20% of the flow field height for this set of parameters.



B. Turbulent flow field (CO_2, high fluid velocity conditions). Note significantly reduced nominal velocity boundary layer thickness (a few % of the flow field height) compared to A.