Equatorial Superrotation on Earth Induced by Optically Thick Dust Clouds

X. Zhu, L. D. Oman†, D. W. Waugh†, and S. A. Lloyd‡*

**JHU Applied Physics Laboratory, Laurel, MD; †JHU Department of Earth and Planetary Sciences, Baltimore, MD; and ‡NASA Goddard Space Flight Center, Greenbelt, MD*

Earth's climate is forced by natural and anthropogenic changes over various time scales, ranging from hundreds of thousands of years (e.g., Earth orbit variations) to a few decades (e.g., fossil fuel burning).

Even much more sudden, dramatic changes can occur, however. It is generally believed that the mass extinction 65 million years ago that included most of the dinosaurs was caused by a super-volcano eruption or collision with a large asteroid, causing a dramatic increase in atmospheric aerosols and a resultant climate shift on the order of months to years. How does the Earth's atmosphere respond to such exceptional aerosol events, and what is the mechanism leading to past and possible future climate shifts?

The presence of an aerosol layer in the atmosphere blocks or reduces the sunlight reaching the surface through absorption and scattering processes and thus produces a direct negative radiative forcing, cooling the Earth's surface. A localized aerosol layer formed either naturally by volcanic eruptions or by anthropogenic injection also modifies the direct local radiative heating within the atmosphere, which alters the atmospheric circulation and produces a secondary, dynamical response in regions that are remote from the forced region.[1] Furthermore, there is also a microphysical indirect effect of aerosols in which aerosols modify the physical-chemical structure of cloud particles and hence the radiative properties of clouds that in turn affect the radiative forcing.[2]

Insights into the impact of exceptional aerosol events on climate change can be gained by studying the problem of Earth's climate change from a perspective of comparative planetary atmospheres, because similar mechanisms control the common phenomenon of dynamics and physics in the atmospheres of other planetary bodies such as Titan and Venus. Comparing and contrasting different atmospheres in the solar system allow us to test our basic understanding of atmospheric processes in general and help us to gain insight into the Earth's atmosphere and its climate change.

One such area of comparative planetary atmospheres is equatorial superrotation. Venus rotates very slowly (rotating only once every 243 Earth days), yet observations of its cloud features indicate that it takes only 4 days for the clouds to circulate around the equator. Therefore, the atmospheric angular velocity on Venus is about 60 times that of the underlying planet! Recent research suggested a more positive linkage between equatorial superrotation and aerosol-induced radiative forcing that generates thermal tides radiating from a heating layer,[3,4] which can be caused by a layer of aerosols, clouds, or dust suspended within the atmosphere. *The major prediction of the model, that Titan's superrotational jet center should be located above about 250 km, has been verified by the recent measurements by the Huygens probe.*[5,6]

Following the theoretical development, a collaborative research effort was initiated between the APL Space Department and the JHU Department of Earth and Planetary Sciences to extend this theoretical result regarding superrotation in planetary atmospheres to the

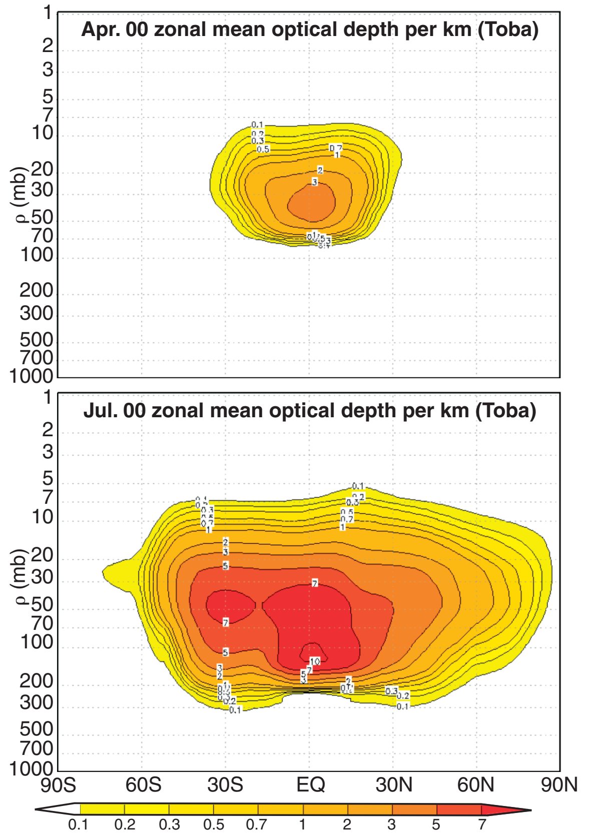

Figure 1. (a) Zonal mean optical depth per kilometer for the Toba simulation for April of year 0. (b) Zonal mean optical depth per kilometer for the Toba simulation for July of year 0.

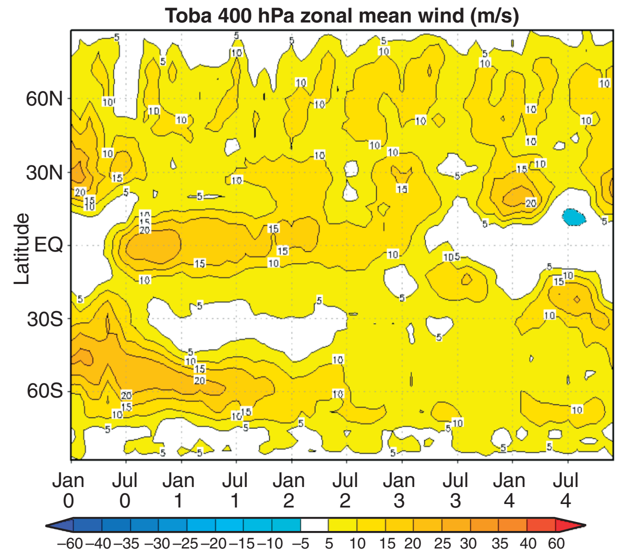

Figure 2. Zonal mean wind (m·s^{-1}) at 400 hPa simulated by using the GISS ModelE general circulation model for the Mt. Toba eruption near the equator that occurred about 71,000 years ago. The equatorial superrotational wind was initiated following the eruption and lasted for more than 2 years.

concept and numerical simulations of superrotation in the Earth's atmosphere. The research served not only to shed insight into the long-standing and seemingly disparate questions of Earth's climate (such as the mechanism of mass extinction and geo-engineering mitigation of global warming) but also to develop a common theoretical framework to address the impacts of profound changes of atmospheric aerosols and their consequences.

The three-dimensional Goddard Institute for Space Studies (GISS) ModelE general circulation model was used to investigate the induction of equatorial superrotation in Earth's stratosphere as well as its effect on meridional transport of dust and aerosols in association with the supervolcano eruptions. One numerical simulation of equatorial superrotation by the eruption of the Toba (Sumatra) supervolcano (ca. 70,000 B.C.) is given in Fig. 1, which shows the growth and spread of the aerosol cloud in the 3-month period after SO_2 was injected during the first week of April of year 0 (over a 7-day period) over the equator into the 25- to 35-km level. An equatorial superrotational wind in the upper troposphere was initiated following the eruption and lasted for more than 2 years (Fig. 2). The circulation structure in the mid-latitude regions also was altered, indicating a global impact of an equatorial injection of an aerosol layer.

The work demonstrates the plausibility of equatorial superrotation on Earth in the context of a sudden, dramatic change. A more detailed analysis of the dynamical consequences of equatorial superrotation for the remainder of the globe (including enhanced meridional transport) is expected to facilitate the estimation of both short-term impact on synoptic meteorology and longer-term impact on climate.

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For further information on the work reported here, see the references below or contact xun.zhu@jhuapl.edu.

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