ATMOSPHERIC OZONE PERTURBATION FROM OCEANIC IMPACTS OF MEDIUM-SIZE ASTEROIDS. E. Pierazzo¹, R.R. Garcia², D.E. Kinnison², D.R. Marsh², M.J. Mills², ¹ Planetary Science Institute, 1700 E. Ft. Lowell Rd., Suite 106, Tucson AZ 85719, U.S.A. (betty@psi.edu), ²National Center for Atmospheric Research, P.O. Box 3000, Boulder, CO 80307-3000, U.S.A. (rgarcia@ucar.edu, dkin@ucar.edu, marsh@ucar.edu, mmills@ucar.edu)

Introduction: Although about 85% of all Near-Earth Objects (NEOs) larger than 1 km in diameter have been discovered, there is still a large number of undiscovered NEOs between 500 m and 2 km in diameter. The collision of NEOs with the Earth is about twice as likely to occur in the deep oceans as in continental areas. We present results of an investigation aimed at characterizing the effects of oceanic impacts of mid-size asteroids on the lower and middle atmosphere [1], by combining simulations with the shock physics code SOVA, to evaluate the injection of material into the atmosphere, and simulations using the Community Earth System Model, version 1.0 (CESM1.0), to characterize the perturbation of atmospheric chemistry.

Impact Simulations: We used the 3D code SOVA [2] coupled with tabular equations of state built from ANEOS [3] to model asteroid impacts into a 4-km-deep ocean. We modeled the impact of idealized spherical asteroids 500 m, 700 m, 1 km and 2 km in diameter, reaching the lower atmosphere with velocities of 12, 18 (most probable), and 25 km/s at an impact angle of 45° from the surface. The simulations started with a spatial resolution of 20 cells per projectile radius around the impact point to accurately resolve the shock wave in the target [4]. As the simulation covered several minutes after impact, the mesh size boundaries were extended upward and outward to follow the expanding impact plume as the resolution decreased. To accurately estimate the water shock state we distributed several hundred thousands of Lagrangian tracers in the ocean around the impact point. The fraction of water vaporized in the impact is determined by the volume of ocean water shocked above 20 GPa [1].

Impact Simulation Results. Large amounts of water are injected in the upper atmosphere over a region that can extend horizontally beyond one thousand km. We assume that liquid water is removed on a short timescale, and is not chemically active. The amount of vapor increases significantly with impactor size and impact velocity. Figure 1 shows the amount of water vapor injected in the upper atmosphere by oceanic impacts of asteroids between 500 m and 2 km in diameter. The oceanic water vapor injected by a 1-km-diameter comet impacting at 25 km/s and 45° is also shown as a red asterisk. In the simulations, no crustal material is ejected in the upper atmosphere by the impacts and only a small component of projectile is entrained in the expansion plume.

Atmospheric Model: To investigate the effects of water vapor injection on the chemistry and dynamics of the atmosphere, we use the CESM1.0, the most recent version of a fully-coupled, global climate model developed at the National Center for Atmospheric Research (http://www.cesm.ucar.edu). CESM consists of geophysical component models (atmosphere, land, ocean, sea ice, and land ice) that exchange boundary data via a coupler. For this study, we used the Whole Atmosphere Community Climate Model (WACCM) [5] as the atmospheric model and the Community Land Model (CLM) as the land model of CESM, with prescribed ocean sea surface temperature data and prescribed sea ice. WACCM is one of a few high-top atmospheric general circulation models that allow for studies of chemical, dynamical and radiative coupling processes between the lower and upper atmosphere. At all altitudes, it incorporates a fully interactive chemical mechanism (65 species) that describes reactions and photolytic processes in the middle and upper atmospheres [6]. WACCM’s vertical domain consists of 66 levels extending from the ground to about 140 km. Both atmospheric (WACCM) and land (CLM) models use a horizontal grid of 1.9° × 2.5°.

Initial Conditions. Impact-released water vapor is introduced as a perturbation in the CESM initial condition, which is taken from available model output for the year 2000. We neglect water in the troposphere, as it

Fig. 1: Water vapor injected in the upper atmosphere (above about 15 km) by oceanic impacts of mid-size asteroids ranging from 500 m to 2 km in diameter. Solid symbols: impacts at 18 km/s. Open symbols: impacts at 12 km/s (lower) and 25 km/s (upper). Asterisk: 1km diameter comet at 25 km/s.
will be quickly removed on a timescale of a few days.

**NOY and Halogens.** The injection of large amounts of nitric oxide, produced by heating of the atmosphere, plus halogens, derived from sea salt contained in vaporized sea water, can produce significant stratospheric ozone depletion. Chlorine and bromine are injected initially as sea salts and then converted into gaseous Cl and Br species [6]. Following the approach of Birks et al. [7] we estimated amounts of impact released NOY, ClY, and BrY as fractions of water vapor released in the impact:

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\begin{align*}
    m_{\text{NO}} & \approx 10^{-3} \times m_{\text{H}_2\text{O}}; \\
    m_{\text{Cl}} & \approx 2 \times 10^{-3} \times m_{\text{H}_2\text{O}}; \\
    m_{\text{Br}} & \approx 3 \times 10^{-6} \times m_{\text{H}_2\text{O}}.
\end{align*}
\]

Chlorine and bromine are initially introduced in WACCM as HCl and HBr [1].

The impact perturbation for a 1 km asteroid was introduced at different latitudes in the Pacific Ocean on Jan. 1, 2000: at the equator, in the subtropics, at 30°N and 30°S, and at high southern latitudes, 50°S. To investigate potential effects of seasonality, the equatorial perturbation was also investigated for a July impact.

**Results:** Initial results show that mid-latitude oceanic impacts of asteroids 1 km in diameter can produce a significant, global perturbation of upper atmospheric chemistry, including multi-year ozone depletions comparable to ozone-hole records registered in the mid-1980s and 1990s [1]. The perturbation remains significant for asteroids larger than 700 m in diameter, while asteroids 500 m in diameter cause limited perturbation of upper atmospheric chemistry with significant ozone depletion confined to the hemisphere in which the impact occurred. Figure 2, showing zonally and monthly averaged ozone column depletions for a 1-km asteroid impacting at 18 km/s with respect to the unperturbed case, demonstrates how impact location affects the atmospheric perturbation. A high-latitude impact causes atmospheric perturbations that are mostly confined to the hemisphere of impact (e.g., 50°S Impact case in Fig. 2), while atmospheric perturbations from subtropical (30°N and S cases in Fig. 2) to low latitude (Equatorial Impact case in Fig. 2) impacts spread to both hemispheres, thus having a global effect. Maximum perturbation occurs for equatorial impacts, causing high latitude ozone depletion of more than 80% in both hemispheres. This behavior may be understood in terms of the characteristics of the mean meridional circulation of the stratosphere, which is composed of two cells, with rising motion in the tropics and descent in the equator. As a consequence, perturbation introduced at high latitudes tend to be swept out of the stratosphere in the hemisphere of injection, whereas tropical perturbation will spread globally. Upper atmospheric ozone concentration shows seasonal variability, especially at high latitudes. However, a summer impact at the equator does not appear to show significant differences in perturbation compared to a winter impact.

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