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## Enhancement of oceanic nitrous oxide emissions by storms

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The world's oceans (including the coastal zones) account for about one-third of the global nitrous oxide (N<sub>2</sub>O) emissions to the atmosphere (IPCC, 2007). In the tropical ocean containing pronounced oxygen minimum zones (OMZs) – such as those found in the Arabian Sea and the eastern tropical North Pacific (ETNP) – maximum accumulation of up to 80 nmol L<sup>-1</sup> of dissolved N<sub>2</sub>O generally occurs at water depths of 50-150 m (Bange, 2008) For comparison: typical N<sub>2</sub>O concentrations in the surface mixed-layer are 5-10 nmol L<sup>-1</sup> (Bange, 2008). However, N<sub>2</sub>O from this upper-ocean maximum is not ventilated to the atmosphere because of stratification. Weather disturbances such as storms can, nevertheless, deepen the mixed layer considerably, thereby entraining N<sub>2</sub>O from the subsurface maximum to the surface layer, where it easily escapes to the atmosphere. This simple scenario of enhanced N<sub>2</sub>O emissions from the ocean caused by strong wind events (such as cyclones in the North Indian Ocean and hurricanes in the East Pacific Ocean) has never been demonstrated because scientific campaigns usually avoid storms. In a recent paper, Naik et al. (2008) provide the first evidence for this phenomenon. These authors could obtain data on vertical distribution of N<sub>2</sub>O in the central Arabian Sea just before and after a cyclone crossed the region in December 1998, and found a significant enhancement of N<sub>2</sub>O concentration in the surface layer along with a decrease in temperature and an enrichment of macronutrients (nitrate and phosphate), all testifying to intense vertical mixing caused by the cyclone. On the basis of their data they calculated that the N<sub>2</sub>O inventory in the upper 50 meters increased by about 2.3 Gg N<sub>2</sub>O following the cyclone. Assuming that an equal amount would already have escaped to the atmosphere (because of the high wind speeds facilitating vigorous air-sea gas exchange) during and shortly after the cyclone

(4-8 days) before the observations were made, we estimate that this single event, which lasted only for 7 days, contributed an extra 1% to the annual Arabian Sea N<sub>2</sub>O emissions of about 500 Gg N<sub>2</sub>O (Bange et al., 2001). The central Arabian Sea on an average experiences 2 cyclones every year (mean calculated from the 1945-2007 data given at [http://weather.unisys.com/hurricane/n\\_indian/index.html](http://weather.unisys.com/hurricane/n_indian/index.html)). Thus, the annual contribution of cyclone-triggered N<sub>2</sub>O should be at least 4.6 Gg yr<sup>-1</sup>. The average hurricane frequency in the ETNP is much higher (14 per year, calculated from the 1949-2007 data given at [http://weather.unisys.com/hurricane/e\\_pacific/index.html](http://weather.unisys.com/hurricane/e_pacific/index.html)). In the ETNP comparable N<sub>2</sub>O accumulation occurs in the shallow subsurface layer. Assuming a similar efflux of N<sub>2</sub>O caused by each cyclone or hurricane, we estimate that a total of about 80 Gg N<sub>2</sub>O is released from the Arabian Sea and the ETNP annually as a result of tropical storms. This amounts to about 1.3% of the global open ocean N<sub>2</sub>O emissions of 6000 Gg yr<sup>-1</sup> (IPCC, 2007). This is a very conservative estimate, however, because the effect of storm events on N<sub>2</sub>O emissions from adjacent ocean areas such as the coastal upwelling in the Arabian Sea has not been taken into consideration, and Cyclone 08A-98, the data for which have been used here, was of a very moderate intensity (maximum wind speed ~120 km h<sup>-1</sup> as compared to, for example, 270 km h<sup>-1</sup> for the super-cyclone Gonu that hit exactly the same area during 27 May - 5 June 2007). Moreover, Patra et al. (2004) used a model to simulate N<sub>2</sub>O emissions from the Arabian Sea triggered by a cyclone (03A-98) in June 1998: They estimated that as much as 40 Gg N<sub>2</sub>O was released to the atmosphere during this single 7-day event (that was intermediate of 08A-98 and Gonu in intensity – maximum wind 185 km h<sup>-1</sup>). This corresponds to about 8% of the annual N<sub>2</sub>O emissions from the Arabian Sea alone, and about 0.7 % of the annual global open

ocean emissions. The global contribution of cyclone-triggered N<sub>2</sub>O emissions from the North Indian Ocean should be even larger when including regions such as the Bay of Bengal (where there is also a large build-up of N<sub>2</sub>O beneath the strongly stratified surface layer (Naqvi et al., 1994) and cyclones are far more frequent and intense than in the Arabian Sea). Therefore, we conclude that N<sub>2</sub>O emissions triggered by strong wind events – cyclones in the North Indian Ocean and hurricanes in the ETNP – contribute significantly to both the regional and global oceanic N<sub>2</sub>O fluxes. This contribution must be included in future model scenarios of oceanic N<sub>2</sub>O emissions.

## References

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