Severe weather conditions in the Arabian Sea and their impact on atmospheric N\textsubscript{2}O budget

Prabir K Patra* & Shamil Maksyutov
Frontier Research for Global Change, 3173-25 Showa-machi, Kanazawa, Yokohama, 236 0001, Japan
* [E-mail: prabir@jamstec.go.jp]

and

Takakiyo Nakazawa
Center for Atmospheric and Oceanic Studies, Tohoku University, Sendai, 980 8678, Japan

Received: 29 August 2003

Influences of tropical cyclones and wide spread south-west monsoon on the ocean-atmosphere fluxes of nitrous oxide (N\textsubscript{2}O) in the Arabian Sea are estimated. The NCEP/NCAR reanalysed wind speeds during a cyclone event are used to calculate N\textsubscript{2}O fluxes from the Arabian Sea. It is found that net emission of N\textsubscript{2}O from the Arabian Sea in a span of about 7 cyclonic days can contribute about 5.3% of its annual sources. This emission rate is about the same as that was observed (earlier estimates) during the south-west monsoon season in the Arabian Sea. The NIES/FRSGC global transport model is used to compute the tracer transport of monthly-mean high resolution fluxes to verify the significance of the Arabian Sea N\textsubscript{2}O emission in comparison with 9 other source types of N\textsubscript{2}O. The results show that the effect of N\textsubscript{2}O flux from the Arabian Sea on its concentration at a coastal station is larger than some of the global scale anthropogenic sources. The transport model simulations suggest that some natural phenomena in the oceanic regions can even produce the fluctuations in the N\textsubscript{2}O time-series observed in the southern hemisphere.

[Key words: Nitrous oxide, Arabian Sea, transport modelling, Indian summer monsoon, tropical cyclones]

[IPC Code: Int.Cl. 7 G01W1/16, C09K3/30]

Nitrous oxide [N\textsubscript{2}O] acts as a greenhouse gas in the troposphere and is the major source of ozone depleting NO radicals in the stratosphere\textsuperscript{1}. N\textsubscript{2}O is about 310 times more efficient in radiative forcing (alternatively defined in terms of Global Warming Potential, GWP) compared to that of the carbon dioxide, the single largest greenhouse gas\textsuperscript{2}. More importantly, the GWP for N\textsubscript{2}O is scaled upward from its previous estimate\textsuperscript{3} of about 200, primarily due to its much larger atmospheric lifetime compared to all other major non-CO\textsubscript{2} greenhouse gases. Recent studies\textsuperscript{2,4} indicate that N\textsubscript{2}O is increasing steadily at the rate of about 0.25% per year since 1980 or at a slightly slower growth rate (~0.18% per year) in the 1990s. These studies support a need for detailed understanding of global and regional source estimations and their variabilities, which directly affect the atmospheric abundance and growth rate of N\textsubscript{2}O.

Nitrous oxide being a biogenic gas, it has both natural and anthropogenic sources on the Earth. Large uncertainties still persist in identifying its individual source strengths and in the estimates of its atmospheric sources and sinks\textsuperscript{5,6}. However, in the recent past the atmospheric source-sink discrepancies have been narrowed down by improving our knowledge of various N\textsubscript{2}O production and consumption mechanisms in the systems of nitrogen cycling\textsuperscript{5}. In this paper, we focus on the observed fluctuations in tropospheric concentration of N\textsubscript{2}O and its implications for the source strength of atmospheric N\textsubscript{2}O and vice versa. It is well known that the anthropogenic sources are smoothly varying over the past years contributing to sustained tropospheric growth rates, whereas the natural sources can vary due to infrequent severe weather changes (e.g. tropical storms, forest fire) or with the changes in large scale meteorological phenomenon such as ENSO (El Niño Southern Oscillation) and summertime monsoon activities (also known as south-west monsoon during June-Sept.) in the Arabian Sea region. Recently an analysis has suggested that a statistically significant correlation exists between the tropical cyclone frequency in the Arabian Sea and the fluctuations in monthly mean N\textsubscript{2}O concentrations at the American Samoa Observatory\textsuperscript{7}.

In this study, we use the simulations of N\textsubscript{2}O fluxes using a three-dimensional tracer transport model to
understand the extent of Arabian Sea fluxes on the global distribution of nitrous oxide. The choice of Arabian Sea for this study is natural due to the well-known seasonal cycle of $N_2O$ super-saturations in the surface water\(^8,9\). The $N_2O$ super-saturations are controlled by the forcing of physical parameters (e.g., mixed layer depth) and biogeochemistry in the sub-surface water (see for example Naqvi et al.\(^{10,11}\)). The sea-air fluxes are primarily driven by the wind speed. Incidentally, all these parameters show large seasonal cycle in the Arabian Sea.

### Methods

The ocean-to-atmosphere fluxes of a solute gas largely depend on the gas transfer velocities (related to wind speeds near the surface) and surface super-saturations of the solute gas. The $N_2O$ fluxes ($F_{N_2O}$) at any location are calculated by using the following relation

$$F_{N_2O} = K_w \cdot \Delta N_2O \quad \ldots (1)$$

where $\Delta N_2O$ is the difference in $N_2O$ concentrations in the surface sea water and marine air, and $K_w$ is the gas transfer velocity of $N_2O$. The values of $K_w$ are calculated for particular wind speed at 10 m height ($U_{10}$) and sea surface temperature (SST) using four different gas transfer schemes\(^{11-14}\). Typically the Erickson (1993)\(^{13}\) model produces largest $F_{N_2O}$ values over a large region, whereas the results using Nightingale et al.\(^{14}\) algorithm stay between those producing lowest $N_2O$ fluxes\(^{11,12}\). In most of the discussions in this manuscript the fluxes derived based on Nightingale et al.\(^{14}\) gas transfer algorithm will be used. In derivation of this algorithm maximum amount dual-tracer observations are utilised and it is also in fair agreement with the widely accepted gas exchange formulations\(^{11,12}\).

A cyclone that occurred during 5-11 June, 1998 over the Arabian Sea is considered as the representative case. The wind speeds at 10 m level from NCEP/NCAR (National Center for Environmental Prediction/National Center for Atmospheric Research) reanalysis data, $U_{10}$, and global climatological SSTs are utilized to calculate $K_w$. The NCEP reanalysis is originally available at 2.5\(^\circ\)x2.5 degrees and SSTs at 2.0\(^\circ\)x2.0 degrees horizontal resolution, and both are interpolated to a common 1.0\(^\circ\)x1.0 degree resolution for this calculation. The cyclone center (coincident with zero wind speed) was located around 14\(^\circ\)N, 68\(^\circ\)E on June 5, 1998, 12 UT and it moves towards the north to cross the Indian coast (not shown). The wind speeds recorded more than 12 m/s on June 5, 1998, 12 UT off the Somali coast, and this high wind speed regime almost covered the complete Arabian Sea as the center of the cyclone moved north-eastwards. In general, the intensity of winds increased with time till June 11, and finally tapers off quickly soon after that.

The $\Delta N_2O$ values are assumed based on our own experience and various published results on the $N_2O$ measurements from the Arabian Sea. In general, the observations revealed large variations in $\Delta N_2O$ in the Arabian Sea surface water. It varies from near zero values during premonsoon\(^{15,16}\) (Mar-Apr-May) to very high values of about 6-12 nmol/L during southwest monsoon season\(^8,16\) (Jun-Jul-Aug). Intermediate levels of super-saturations are found in the postmonsoon (Sep-Oct-Nov) and northern hemisphere winter (Dec-Jan-Feb) seasons\(^{17,19}\). In addition, water that experiences coastal upwelling or winter-time overturning in the northern Arabian Sea\(^{10,17,18}\) exhibit even larger values of $\Delta N_2O$ (values larger than 10 nmol/L). It is known that strong vertical mixing in the mixed layer (~100 m) occurs under the cyclone eye\(^{20,21}\). This could also result in identical values of $\Delta N_2O$ in the central Arabian Sea as the subsurface water is always rich in $N_2O$. However, as the measurements covering both spatio-temporal variability of $N_2O$ are sparse, it would be rather unrealistic to interpolate or extrapolate the $\Delta N_2O$ estimates for the whole Arabian Sea. It may also be noted here that there are no measurements available during a cyclonic storm from this region, to best of our knowledge. On the other hand, an analysis, mathematically robust but limited by actual measurements, has been performed recently to produce a gridded distribution of $N_2O$ concentrations in the surface waters of Arabian Sea\(^9\). The saturation $N_2O$ values are estimated using the parametric relation as a function of the climatological SSTs, salinity and an atmospheric $N_2O$ concentration of 312 ppb. This latitude-longitude distribution of $\Delta N_2O$ and a constant value of 2 nmol/L are used as two test cases in the estimation of sea-air fluxes of $N_2O$.

The NIES (National Institute of Environmental Studies, Tsukuba)/FRSGC global atmospheric transport model\(^{22}\) is used to simulate the distribution of $N_2O$ for a source limited to the Arabian Sea region. The 1x1 degree flux distributions for the Arabian Sea are used from the above calculation. This tracer...
transport model is also used to simulate the signals from the monthly mean global emission maps of N₂O from several other source types. The details of this transport model is described elsewhere, and only a brief description is given here. The continuity equation for an atmospheric trace constituent is solved. A first order advection scheme is used to solve for the semi-Lagrangian tracer transport. The model uses monthly averages of daily planetary boundary layer depth, and the vertical redistribution of tracers by cumulus convection is parameterised by a Kuo-type scheme. The model has 2.5×2.5 degrees horizontal resolution and 15 vertical sigma layers. The model meteorology was driven by the European Centre for Medium-Range Weather Forecasts (ECMWF) operational analysis for a climatological year 1997. This model version does not account for losses of N₂O in any form; thus the simulated trends or actual concentrations will not be calculated here. However, the relative importance of different source types can be studied. Due to this limitation we shall be using arbitrary units in the discussions.

Results and Discussion

Figure 1 shows the distribution of nitrous oxide fluxes from the Arabian Sea, calculated using the gas transfer scheme of Nightingale et al. This scheme is known to produce an intermediate flux transfer rates among the four gas transfer schemes used here. On 6 June 1998, 12 UT, N₂O fluxes are higher in Somali Basin, reaching up to 1.4 pg/cm²/s, over a small region, and its low values (below 0.2 pg/cm²/s) are predominant over large area of the Arabian Sea. The other two pockets of high to very high flux regions are located along the Indian west coast and these are associated with very high ΔN₂O values. This part of the Arabian Sea experiences strong coastal upwelling during JJA season of the Indian summer monsoon and thus the high emission rates (~2.5 pg/cm²/s) can be persistent over a longer time period. As time progresses, it can be seen that the area covered by lower flux rates is reducing and higher flux rates (green for 1.0 pg/cm²/s) are spreading longitudinally across the Arabian Sea. This spread towards the higher latitudes is relatively slow. Finally, high emission rates are widespread in the whole Arabian Sea which peaks around 2.0 pg/cm²/s off the Oman coast on 10 June 00 UT. The N₂O fluxes using other two gas transfer schemes also show fairly similar distributions of relative intensities in N₂O sea-air fluxes. The derived flux distribution with the spatially homogeneous ΔN₂O = 2.0 nmol/L shows close correlation with the winds speed distribution following Eq. 1.

Using the sea-air flux distributions of N₂O in the Arabian Sea, the net emission rates in the period of 04 June 00 UT to 11 June 18 UT are estimated from the total area of the Arabian Sea (seen as coloured region in Fig. 1), which accounts for about 6.5 km² (~1.7% of world oceans). The net N₂O fluxes are calculated to be about 0.019, 0.033, 0.082, and 0.026 Tg N₂O-N/cyclone, respectively, while the gas transfer schemes of Liss & Merlivat, Wanninkhof, Erickson, and Nightingale et al. are used. These values are estimated to be in the range of 0.4-1.3% of the global annual oceanic emissions rates estimated using the same gas transfer schemes, and an average of about 5.3% of the annual emissions from the Arabian Sea alone. The gross flux estimations over the cyclonic storm are lesser by about 25% when the constant ΔN₂O value of 2 nmol/L is used. The net emission due to a single cyclone storm appears significant in all respects. In addition, a separate calculation indicates that such high flux rate (per day) is quite similar to that is estimated for the JJA season for the Arabian Sea. Since the high wind speeds as well as the high ΔN₂O values are prevalent during the whole JJA season, we will extend the simulations using the transport models with the seasonal scale fluxes of N₂O. The use of fluxes during 7 cyclonic days (i.e. over a shorter period) will only shorten the simulated peak widths and reduce the peak heights proportionally. All other aspects such as the delay between the emission in Arabian Sea and response signal between different locations, and their relative signal strengths will remain fairly similar.

Before going into the transport model simulations of fluxes from the Arabian Sea, it is worthwhile to discuss briefly the general trends and features observed in the time-series of N₂O. The data on N₂O distributions are obtained from the Climate Monitoring and Diagnostic Laboratory (CMDL), Boulder, Colorado global network. In Fig. 2, the variability in N₂O concentration during the period 1995-2002 are shown; which depict a gradual increase in the concentration globally. However, it is also noticeable that there are fluctuations over-riding the monotonous increase. The fluctuations are also larger and distinct in the case of stations in the southern hemisphere (SH) (on an average or at the American Samoa Observatory/SMO in particular) compared to those in the northern hemisphere (NH) (on an average
or at Mauna Loa Observatory/MLO). This may indicate that the fluctuations in N$_2$O abundances are caused by the natural variations in the atmospheric conditions since the sources of N$_2$O in the SH are predominantly of the natural origins. The N$_2$O abundances in the NH are controlled mostly by the anthropogenic sources. The trajectory analysis using the ECMWF meteorological data at 850 mb suggests that a part of the variability observed at SMO stations is caused by the interannual variations in the inter-hemispheric transport. The N$_2$O concentration variations in the middle-upper troposphere are also free from direct anthropogenic influence over some locations and the increase rate is apparently under the control of the stratospheric quasi-biennial oscillation (QBO).

The simulated N$_2$O distributions by using NIES/FRSGC tracer transport model due to the monthly mean fluxes, emitted in the period of June-July-August (JJA) from the Arabian Sea, are depicted in Fig. 3. The computations clearly indicate that the air mass quickly get mixed along the equatorial longitudes, and then transported to the higher latitude regions in both the hemisphere. While the surface concentrations (see Fig. 3 A-D) spread over the Indian subcontinent by the south-westerly trade winds, the transport of N$_2$O is much faster through the upper tropospheric circulation. During this period of time the monsoonal circulation set up a upward motion near the Tibetan Plateau and a downward motion in the high pressure region of continental Africa. The coupling between Asian summer monsoon low pressure regime and the Azorean high is suggested as the mechanism of pollution transport from Asia to the Mediterranean. Our simulations also indicate the possibility of such crossroads between the Indian

Fig. 1—Fluxes of N$_2$O (in pg/cm$^2$/s) from the Arabian Sea derived from $\Delta$N$_2$O distribution map corresponding to the JJA months. The diagram depicts the effect of wind speeds as well as the N$_2$O surface super-saturations on evasion flux. These emission rates are used to estimate the net sea-air fluxes of N$_2$O during the whole cyclone event.
subcontinent the Mediterranean Sea region during the boreal summer. Comparison between the panels on the left and right in Fig. 3 suggest that the flux signal from the Arabian Sea is transported faster at 500 mb than that near the ground. It is yet unknown whether this N$_2$O source-signal can be detected in the relatively less polluted air in the upper troposphere over the sea of Mediterranean.

The detection of N$_2$O source signal at the observation sites depends on the proximity of the measurement stations to the Arabian Sea and the link between the two through the atmospheric transport. Figure 4, shows the time-series of simulated tracer signals at Cape Rama-India (CRI), MLO, and SMO sites. The selection of CRI station is made here due to the fact that the atmospheric research division of CSIRO (Commonwealth Scientific and Industrial Research Organisation, Australia), in collaboration with the Indian scientists, carried out weekly flask sampling from this location. Secondly, since CRI is located on the Arabian Sea coast it would record the largest effect of any perturbation in that oceanic region. Results on N$_2$O abundances are not available currently to verify our model simulations but there remains a certain possibility to check it in the future.

As expected, the signal from a cyclonic storm is stronger (forming a peak with sharp increase and decrease) in the vicinity of the Arabian Sea at the Cape Rama station (west coast of the Indian subcontinent) around the emission period. The signal is diluted (marked by a rather slow increase and almost no decrease afterwards) and delayed the most at SMO station, essentially giving rise to a negligible concentration increase. The effect of N$_2$O emission in

Fig. 2—Timeseries of nitrous oxide (in ppb) in the southern hemisphere (average and at American Samoa Observatory/SMO; 14.3'S, 171.6'W) and northern hemisphere (average and at Mauna Loa Observatory/MLO; 18.7'N, 156.3'W) (source: CMDL).
Fig. 3—The N$_2$O (arbitrary unit) tracer transport simulations by using the NIES/FRSGC global model of an emission flux in JJA months (surface: panels on the left, and 500 mb: panels on the right) over the Arabian Sea region. Apparently the reminiscence of the N$_2$O emission from the Arabian Sea can be seen peaking in the SH tropics after about 3 months.
the Arabian Sea reaches about 3 months later to the SMO site. An intermediate level of signal dilution is observed at the MLO station. The intensity of the observed N$_2$O peaks at MLO or SMO (from CMDL data) is difficult to compare with the simulated values. The detection of such natural signals in N$_2$O time-series data may also be suppressed by the variability in the other types of sources such as the biomass burning. The variation in this source is highly coupled to the meteorological factors, e.g. the El Niño Southern Oscillation (ENSO), which has large impact on the monsoonal rainfall over many tropical countries in Asia. For instance the large scale forest fire in Indonesia during 1998 is largely viewed as one of the manifestations of the strongest ENSO event in that decade. The increase in N$_2$O abundances towards the later half of 1998 in the NH and SH could be suggested as the result of Indonesian forest fire event. Multi-species observations of CO$_2$, CH$_4$, CO, H$_2$ etc. have strongly suggested the signature of biomass burning footprints in the atmospheric measurements.

We have simulated the global distribution of monthly mean flux climatologies of nitrous oxide by the NIES/FRSGC transport model. The simulated results (or the “signals”) of different source types as captured at three station locations (CRI, MLO, SMO) are shown in Fig. 5. The panels show behaviour of different source signals during a 20-month period of simulation. The variability in each source signals do not exhibit interannual differences since both the meteorological fields (representing year 1997) and the monthly mean source distributions are climatological averages. Also since the signals are shown in arbitrary units, the contributions of each source types are discussed only in relative terms. However, the interesting point in this plot is the differences among the time-series of sources. The N$_2$O signals due to agricultural waste burning (AGWB, Fig. 5A), biofuel burning (BIOF, Fig. 5C) or animal excreta (EXCR, Fig. 5E) are clearly much higher at CRI station compared to the other two background stations at MLO and SMO. This is because these three source types have quite strong emission in the Indian subcontinent. The signals also show very large seasonality-while the emission due to AGWB peaks in January the BIOF and EXCR emission peaks around October at the Indian station. The fossil fuel (Fig. 5F) and industrial emission (Fig. 5G) signals generally appear higher at the MLO site and is much lower at the SMO site, since these two sources are of anthropogenic origin and spatial distribution shows largest emission around the NH midlatitudes. The oceanic flux (Fig. 5H), on the other hand, shows largest seasonality at the SMO station, which is located away from the sources due to human activities and is probably under the largest influence of the natural sources.

To estimate the amount of natural source variability required to produce the fluctuations in SMO data, we moved the N$_2$O emission region from the Arabian Sea to the eastern Pacific region off the Peruvian coast. The estimated surface N$_2$O values are also very high in this particular oceanic region round the year (see Nevison et al. for details). It is seen that the formation of a peak in the time-series of N$_2$O abundance at SMO station is fairly well reproduced (not shown). The intensity of the simulated peak and its shape is similar to those are most frequently observed at SMO immediately after a few days from the start of emission period. However, we are unable to attribute a physical process that could lead to such interannual variability in N$_2$O emission in the neighbouring regions of American Samoa Island. For instance, the most prominent oceanic and atmospheric variations in this region relating to ENSO do not show an unambiguous correlation with the N$_2$O distribution at SMO. This study only hints a possibility of a coupled meteorological phenomenon occurring in two...
Fig. 5—Time-series of different N$_2$O source simulations (arbitrary unit) are shown. The source signals at CRI (empty circle), MLO (filled circles) and SMO (empty square) stations from various source types are shown in Panel-A: Agricultural waste burning (AGWF), B: Biomass burning (BIBU), C: Biofuel burning (BIOF), D: Deforested enhanced soil (DEFR), E: Animal excreta (EXCR), F: Fossil fuel burning (FOSF), G: Industrial sources (INDU), H: Oceanic sources (OCNF), I: Soil under natural vegetation and fertilized agriculture (SOIL), J: Total of all the above source types (TOTL). Due to the use of arbitrary units this plot cannot be compared directly with Fig. 2, but the relative contributions of each source types to the N$_2$O distribution can be studied.
major oceanic regions with a lead-lag phase of about 3-months. However, such a study needs further investigations.

Now, we compare the size of the N$_2$O source in the Arabian Sea in the JJA period with its other forms of sources mostly predominant in the Indian subcontinent, e.g. the animal excreta, biofuel burning and agricultural waste burning. The global total of these sources are about 1.02, 0.13, and 0.09 Tg N$_2$O-N per year. Thus the N$_2$O fluxes of the order of 0.35 Tg N$_2$O-N per season (JJA period; 0.026 Tg N$_2$O-N/7days is scaled to 92 days) from the Arabian Sea only is quite high in terms of the flux density. The effect of this high flux density is apparent from the panels in Figs. 4 and 5. While the monsoonal flux signal shows very large and sharp peak, the others show slower rise in concentration and lesser peak heights. The other way to measure the relative significance of different source types is by estimating the effective growth rate caused by a particular source type. It is clearly seen from the Figs. 4 and 5 that an identical annual/baseline growth rate (~0.05 unit/3 years) was observed at the three measuring sites (CRI, MLO and SMO) due to the N$_2$O flux from the Arabian Sea, which resides between those estimated due to fossil fuel burning (~0.06 unit/3 years) or industrial emission (~0.1 unit/3 years) and agricultural waste burning (~0.015 unit/3 years) or biomass burning (~0.02 unit/3 years). Though the net emission from fossil fuel burning (29.4 Tg N$_2$O-N per year) and industrial sources (43.7 Tg N$_2$O-N per year) are much larger compared to the Arabian Sea emission, the influences of these sources vary with location. Since the former two emissions are mostly found in the land of NH midlatitudes, their effect on the N$_2$O concentrations at CRI, MLO and SMO reduced gradually. This effect is also seen in Fig. 5F, where a clear difference in the simulated signal baselines at CRI, MLO and SMO can be seen. On the contrary, the emission in the Arabian Sea is mixed quickly in the equatorial region and result in similar baseline values at all the three stations. For the relatively short-lived gases, such as methane (CH$_4$), carbon monoxide (CO), ozone (O$_3$), hydrogenated

Fig. 6—Seasonal cycles of N$_2$O (in ppb) at CRI, MLO and SMO for total source with and without the source in Arabian Sea included. Ideally one should replace the oceanic flux from this region by the flux distribution used in this work during JJA months to see the real impact of the Arabian Sea source on N$_2$O concentrations and peak formation. The simulated signals are normalised with respect to the seasonal cycle at the South Pole station (89.98ºS, 25ºW).
chlorofluorocarbons (HCFCs) etc., the source signal distributions are likely to be confined more locally.

Figure 6 shows the comparisons between the seasonal cycles with (dashed line) or without (continuous line) the source of N\textsubscript{2}O in the Arabian Sea during JJA season with respect to the South Pole station. It is seen that a peak is created at the CRI station prior to the primary peak in October month during which most of the other N\textsubscript{2}O sources contribute to the increase in concentration (see Fig. 5 for details). The height of this peak is about the half of the primary peak. This result suggests that source signal as large as the Arabian Sea during south-west monsoon could be detectable at a closely located observation station. At the MLO and SMO stations only a small shift in the background concentration is observed.

Conclusion

The tropical cyclones and the south-west monsoon trigger a strong source of nitrous oxide in the Arabian Sea. This source can be significant in the global N\textsubscript{2}O budget. Particularly, the monsoon activity during June-July-August period can have significant impact on the N\textsubscript{2}O distribution in the Indian subcontinent. The Arabian Sea source signal (for 3 month period) is stronger than that can be simulated with the sources from agricultural waste burning or biomass burning globally. Therefore, it can be said that any climate systems, e.g. ENSO or other decadal scale oscillations, those have influence on the large scale weather systems, such as the Indian Summer Monsoon, may modulate the N\textsubscript{2}O concentrations near the source region. Since the anthropogenic perturbations are typically larger than these natural variabilities in the northern hemisphere midlatitudes, such perturbations are likely to remain undetected there. As in the transport model simulations only climatological flux functions are used for N\textsubscript{2}O much conclusions cannot be made about the interannual variability in its concentration time-series. Further detail understanding of the controls on N\textsubscript{2}O emission is also needed to produce interannually varying flux functions.

Acknowledgement

We are grateful to the HATS group at CMDL for putting up the observational data on the Internet (www.cmdl.noaa.gov), some of which are utilised here. The gridded N\textsubscript{2}O distributions in the Arabian Sea are provided by Hermann Bange and the data are archived at the German JGOFS data management centre (www.ifm.uni-kiel.de/jgofs/dm). The monthly mean global emission maps of N\textsubscript{2}O are obtained from Lex Bouwman, and we appreciate his help. The NCEP/NCAR Reanalysis data are provided by the NOAA-CIRES Climate Diagnostics Center, Boulder, Colorado, USA.

References


27 Maksyutov S & Patra P K, Results based on trajectory analysis (unpublished data).

