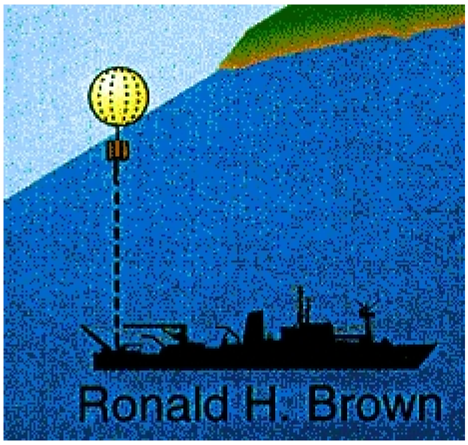
INDOEX



Short Description of the Indian Ocean Experiment (INDOEX)

D. Kley and H.G.J. Smit
Institut für Chemie und Dynamik der Geosphäre (ICG-2)
Forschungszentrum Jülich
Postfach 1913, D-52425 Jülich

Introduction

The interaction between ocean and atmosphere is the main reason for natural climate changes on time scales of months to decades. The interaction plays an important role in climate models, where the processes with spatial and time scales to small to be represented explicitely, have to be parameterized. In the tropics Cumulonimbus (Cb) convection contributes more than 50% to the energy budget of the Hadley circulation. The extent of the undiluted cores of Cb convection is only about 25 km^2. Their number in the tropical trough region is 1600-2000 altogether at any time, so that the transport of energy takes place in only 0.1% of the area of the equatorial trough. The upward velocity in Cumulonimbi is about 2-3 m/s. Because of the small spatial scale and the resulting enormous need of computer capacity it will be impossible for a long time to calculate climate models on spatial and time scales comparable to Cb convection.

More important than the limitation because of computer capacity is the still badly understood physics of Cb convection. Besides, the ocean-atmosphere coupling needed to be known better to describe Cb convection quantitatively. The most important unknown characteristics are the interactions between sea surface warming, radiative cooling of the sea surface, evaporation and Cb convection.

While the energetics of these processes is not clear sufficiently neither on the micro nor on the macro scale, there is even less knowledge about the transport processes related to convection. Water vapor contributes to the natural greenhouse effect by more than 80%. Despite this outstanding importance of water vapor for the climate, significant details of the vertical transport processes of water vapor are still unknown. There is, for example, a scientific dispute on the question whether Cb convection moistens or dries the upper tropical atmosphere.

Another subject with many unknown details regarding climate are clouds. The influence of clouds on climate has one of the major uncertainties in the attempt to predict future climate change. There is no doubt Cb convection is caused through sea surface warming and the air in the convective region is loaded with water vapor. Since water vapor absorbs the infrared radiation of the sea surface, Cb convection leads to further heating of the regions with Cb convection. The result is a positive feedback called the super greenhouse effect. This effect was measured directly for the first time during the **C**entral **E**quatorial **P**acific **Ex**periment (CEPEX). CEPEX has also identified processes that limit the super greenhouse effect. The super greenhouse effect leads to an enlargement of the Cirrus cloud layer which reflects the solar radiation and keeps the sea surface temperature from rising further. This is the thermostat hypothesis of Ramanathan and Collins (1991) in short terms. The Hypothesis is able to explain two observations that are important for the present climate:

1. Why is the maximum sea surface temperature so close to 300K, the threshold for Cb convection?
2. Which processes limit the temperature to 300K?

The thermostat hypothesis states that when the sea surface temperature (SST) reaches a certain value, Cb convection starts. The Cirrus layer that covers thousands of km^2 is able to reflect enough solar radiation to keep the SST near 300K. The CEPEX experiment has made a major contribution to a hypothesis that is discussed controversely today. At the same time (Science, 27 January 1995) two articles where published (Ramanathan et al., Cess et al.). Cess et al. showed, that at 5 geographically different measurement points the absorption of solar radiation through clouds was about $25 Wm^{-2}$ higher than predicted by theoretical models. Ramanathan et al. describe similar findings during CEPEX over the tropical Pacific. They conclude that the shortwave radiative forcing by clouds is large in this region, about $100\ Wm^{-2}$. This value is 1.5 times higher than at the top of the atmosphere.

The above results will have, in case they are correct, very important implications for the circulation models used in climate research.

Atmospheric Chemistry and Chemical Transport

During CEPEX Kley et al. (Science, 11 October 1996) have made an important observation regarding the ozone content of the troposphere over the central equatorial Pacific. In this region the NOx concentrations close to the surface are remarkably low, so that there is no photochemical ozone production, resulting in almost ozone free air in the marine boundary layer (MBL). Several measurements showed ozone concentrations below 10 ppb. Still, the observation of very low ozone concentrations in the uppermost layers of the troposphere in regions with strong convection was surprising. The main explanation is the fact that Cb convection is able to transport air masses from the MBL directly, without mixing, to the upper troposphere. On one hand the low ozone concentrations are a tracer for the nature of Cb convection. On the other hand there are important implications for the chemistry of the troposphere. Comparing the chemical lifetime of oxydable substances to the time scale of vertical transport, one can find that even shortlived species like the important dimethyl sulfid ($(CH_3)_2S$) can get into the upper troposphere in regions with strong convection. There they can oxydize to aerosoles which act as cloud condensation nuclei (CCN).

Relation to Physical Oceanography

Considering the radiative and dynamical processes that couple the sea surface to the atmosphere we have to take a deeper look at the uppermost layer of the ocean. In reaction to atmospheric influences like wind, solar radiation, and the infrared radiation that is modified by clouds the state of the sea surface layer changes (turbulence, temperature profile, salt content, etc.). To really understand the processes described above and the interactions, the physical processes in the sea surface have to be measured quantitatively.

Ocean - Atmosphere Coupling

The study of the ocean-atmosphere coupling includes three different disciplines of earth sciences: climate research, physical oceanography, and atmospheric chemistry. To predict climate change, of natural as well as anthropogenic origin, the statements of climate models have to be applied. Besides the investigation of processes needed to understand the present state of the climate, the reaction of the system on external influences is necessary to predict climate. It is generally accepted that the answer of the climate system on nonlinear positive and negative feedback is difficult (if at all) to deduce from the present state. Nevertheless, the thorough understanding of the present state, based on detailed investigations of single processes and mechanisms, is an essential requirement for the building of better climate models and the right way to find the timedependence of the system. CEPEX focussed on the natural atmosphere of the central pacific without anthropogenic pollution. The CEPEX results give important insight in the dominant role of water vapor for the greenhouse effect. Yet, they do not allow conclusions about possible results of anthropogenic influences.

The Indian Ocean Experiment (INDOEX)

Based on the findings of CEPEX, especially the thermostat hypothesis, the excessiv solar absorption by clouds, the 'short circuit' between MBL and uppermost troposphere, and completed by observations of the anthropogenic radiative forcing through sulfate particles the Indian Ocean Experiment (INDOEX) was proposed by a group of scientists. (V. Ramanathan, P.J. Crutzen, M.O. Andreae, J. Coakley, R. Dickerson, J. Heintzenberg, A. Heymsfeld, J.T. Kiehl, D. Kley, T.N. Krishnamurti, J. Kuettner, J. Lelieveld, S.C. Liu, A.P. Mitra, J. Prospero, R. Sadourny, A.F. Tuck and F.P.J. Valero)

Goals of INDOEX

INDOEX is a field experiment focussing on the Indian Ocean, aiming on a deeper understanding of the interaction between ocean, atmosphere and radiation. INDOEX is based on the above mentioned results of CEPEX. In INDOEX it is tried to find contributions to the following three connected subjects:

1. The assessment of the importance of sulfate and other continental aerosoles on the radiative forcing.
2. The determination of the amount of solar absorption at the sea surface and in the troposphere (including the cloud systems of the Intertropical Convergence Zone (ITCZ).
3. The investigation of the role of the ITCZ in the vertical transport of atmospheric trace gases, including anthropogenic substances, and the resulting radiative forcing.

The INDOEX white paper contains further information on the subjects mentioned above.

Platforms

Apart from surface based and satellite measurements several aircraft will be used during INDOEX. Besides, there will be two research ships: The American research ship 'Ronald Brown' and the Indian research ship 'Sagar Kanya. The different platforms are not redundant.

References

Cess, R.D., M.H. Z/hang, P. Minnis, L. Corsetti, E.G. Dutton,B.W. Forgan, D.P. Gar-ber, W.L. Gates, J.J. Hack, E.F. Harrison, X. Jing, J.T. Kiehl, C.N. Long, J.J. Mor-crette, G.L. Potter, V. Ramanathan, B. Subasilar, C.H. Whitlock, D.F. Young and Y. Zhou, Absorption of solar radiation by clouds: observation versus model, SCIENCE, **267**,496-499, 1995.

Kley, D., P.J. Crutzen, H.G.J. Smit, H. Vömel, S. Oltmans, H. Grassl, V. Ramanathan. Observations of Near-Zero Ozone Levels Over the Convective Pacific: Effects on Air Chemistry. SCIENCE, 274, 230-233, 1996.

Kley, D., Tropospheric Chemistry and Transport, Science, 276, 1043-1045, 1997a.

Kley D., H. G. S. Smit, H. Vömel, H. Grassl, V. Ramanathan, P. S. Crutzen, S. F. Williams, S. Meywerk and S. Oltmans,.Tropospheric Water Vapour and Ozone Cross Sections in a Zonal Plane over the Central Equatoral Pacific. Quart. J. Roy. Met. Soc. 123, 2009-2040, 1997b.

Ramanathan, V. and W Collins, Thermodynamic regulation of ocean warming by cirrus clouds deduced from observations of the 1987 El Nino. Nature **351**, 27-31, 1991.

Ramanathan, V., B. Subasilar, G.J. Zhang, W. Conant, R.D. Cess, J.T. Kiehl, H. Grassl, I: Shi, Warm pool heat budget and short wave cloud forcing: a missing physics? SCIENCE **267**, 499-503, 1995

Informationen über INDOEX im Internet:

About the Center for Clouds, Chemistry and Climate (C^4)	http://www-c4.ucsd.edu/
About INDOEX	http://www-indoex.ucsd.edu/
About INDOEX-Shipcampaign on Research Vessel "Ronald Brown"	http://www.metolab3.umd.edu/~russ/INDOEX.ship.html

Vertical Soundings of Ozone and Water Vapor in the Equatorial Region of the Indian Ocean

[Contribution of the ICG-2 to the Indian Ocean Experiment (INDOEX)]

H. G.J. Smit und D.Kley
Institut für Chemie und Dynamik der Geosphäre (ICG-2)
Forschungszentrum Jülich
Postfach 1913, D-52425 Jülich

Goals of the Project

The intended vertical soundings of ozone and water vapor are aiming at one of the fundamental goals of climate research: the understanding of the interaction between the warm ocean surface, convection and it's influence on the distribution of water vapor in the upper troposphere. The measurement of ozone serves as a diagnostic tool for the identification of Cumulonimbus convection. In addition, the vertical profiles of ozone and water vapor are used to determine the oxidative capacity of the troposphere. They are needed to calculate the reaction rates of reduced substances ($(CH_3)_2S$, SO_2, etc.). The oxidation products of these substances are precursors for condensation nuclei. This project is implemented in the multinational Indian Ocean Experiment (INDOEX), a field experiment wich focusses on the Indian Ocean and aims on a deeper understanding of the interaction between ocean, atmosphere and radiation.

Previous Findings

INDOEX is based on the results of CEPEX (Central Equatorial Pacific Experiment). Both field experiments focus on the coupling between ocean and atmosphere, one of the most important parameters influencing climate and it's natural variability through the interaction of cloud formation, aerosols, and atmospheric chemistry. The influence of clouds on climate is one of the biggest uncertainties in the attempt to predict future climate changes. Water vapor is the driving force for these clouds and it contributes more than 80% to the natural greenhouse effect. But despite this outstanding importance of water vapor for the climate, significant details of the vertical transport of water vapor through Cumulonimbus (Cb) convection are still unknown. Cb convection in the tropics provides more than half of the Hadley circulation energy budget by transporting water vapor and clouds and is therefore extremely important for climate forcing. During the CEPEX , 1993, the so called "super greenhouse effect" was measured directly for the first time. It is a positive feedback between the Cb convection which is coupled to the sea surface temperature (SST) and the greenhouse effect caused by water vapor that is able to rise the SST. But also during CEPEX processes where identified that can limit this positive feedback. For example the so called thermostat hypothesis by Ramanathan and Collins (1991): "When the SST rises above a threshold (>300K), Cb convection starts and leads to a Cirrus layer that spreads over several thousand km^2. The Cirrus clouds reflect parts of the incoming solar radiation and prevent the SST from rising to more than 302K."

Whether Cb convection moistens or dries the tropical atmosphere is still controversally discussed. As water vapor contributes more than 80% to the greenhouse effect, this is a major uncertainty that has to be clarified with the help of reliable in-situ measurements of atmospheric water vapor in regions with active Cb convection. One of the problems arising with these measurements is the fact that frequently the infrared radiation temperature or the reflection properties of clouds are used to identify Cb convection. In this case the dependent variable (water vapor) can not be separated from the independent variable (convection).

In CEPEX and previous works we (Kley et al., 1996, 1997 a, b) have shown the reliability of ozone as an indicator for Cb convection. This diagnostic tool is based on the fact that the ozone concentration over the tropical ocean is very low due to the lack of photochemical sources. Cb convection lifts the airmasses that are low in ozone into the Region of the spreading anvils. The morphology of the resulting "ozone holes" identifies the intensity and spatial distribution of Cb convection reliably. Therefore the in-situ measurement of ozone gives additional information on Cb convection independent of the radiation measurements, even if the anvil is already optical thin through dissipation.

During CEPEX we (Kley et al., 1996) made an important discovery regarding the ozone content of the central equatorial Pacific troposphere. In this region the NO_x concentration is remarkably low, suppressing photochemical ozone production. This leads to almost ozone free air in the marine boundary layer (MBL). Mixing ratios not exceeding 10 ppb where measured frequently. Still, the observation of very low ozone concentrations in the uppermost layers of the troposphere was surprising. It is explained mainly by the fact that Cb convection can lift air directly from the MBL in the upper troposphere without mixing. This leads to important implications for the chemistry of the troposphere. Considering the timescale of vertical transport of MBL air under this circumstances, even chemically shortlived substances like dimethyl sulfid ($(CH_3)_2S$) can reach the upper troposphere in regions with strong Cb convection. There they can form aerosols by oxidation which act as cloud condensation nuclei (CCN).

Ozone and Water Vapor Soundings During INDOEX

To investigate the ozone and water vapor distribution in the equatorial regions of the Indian Ocean during INDOEX ozone/water vapor soundings will be conducted during 40 days in February/March 1999. It is planned to launch small balloons (2 m^3) with calibrated ozone/humidity sensors every 12 to 24 hours from the American research ship "Ronald Brown" during the entire field campaign. This will provide ozone and humidity data of previously unattained accuracy and precision. The cruise will be confined mainly to the equatorial part of the Indian Ocean to guarantee a representative cross section of ozone and water vapor in that region.

The main components of the ozone sonde system used used are the ozone sensor, a radio wheather sonde, an interface between both, the balloon, and batteries. A complete data set of measurements of ozone, pressure, temperature, and humidity is transmitted on board the ship every 7 seconds and is processed and stored on-line. The total weight of the balloon sonde is about 1000 g. It can reach a vertical velocity of about 5 m/s and a height of 30 to 35 km. The total cost of a balloon sonde is about 1,250 DM.

To measure the vertical profiles of ozone accurately ozone sondes that are calibrated in our laboratory will be used. The Institut fuer Chemie und Dynamik der Geosphaere houses the "World Calibration Center for Ozone Sondes", a climate chamber sanctioned by the WMO, to test and calibrate ozone sondes under simulated flight conditions (Smit et al., 1994). The utilized humidity sensors, Humicap-H sensors of the RS80 radiosonde (Vaisala, Finnland), are also calibrated in our climate chamber against a reference instrument.

Postcampaign work (April 1999 to December 1999) will be mainly the preparation and validation of the INDOEX sounding data by using the results of the sensor calibration in the simulation chamber. Together with the soundings large scale meteorological data (ECMWF analysis) and IR remote sensing data (SST, cloud coverage, CTT, etc.) will be provided and an initial analysis and interpretation of the results will be conducted. The results will be contributed to the INDOEX database at the end of 1999.

In preparation for INDOEX we have conducted 15 ozone/water vapor soundings in cooperation with the Indian National Physics Laboratory (NPL) in March 1998 on board the Indian research ship "Sagar Kanya" over the Indian Ocean. The sondes were provided by us and operated by the Indian colleagues. At present we are analysing the results for further planning of the INDOEX soundings for Februrary/March 1999.

The ozone/water vapor sounding program will be an important contribution to understand the interaction between the warm ocean surface, Cb convection, oxidative condition, and the distribution of water vapor in the upper troposphere. Until now, there are no reliable measurements of water vapor and ozone in the upper troposphere above the Indian Ocean, and no independent parameter to identify Cb convection. The determination of the oxidative condition of the troposphere will focus on the formation of cloud condensation nuclei by oxidation of reduced substances ($(CH_3)_2S$, SO_2, etc.).

Since CEPEX (1993) there is a close scientific cooperation between ICG-2 and the American Center for Clouds, Chemistry and Climate (C^4) of the Scripps Institution of Oceanography, San Diego (director: Prof. V. Ramanathan) emphasizing the study of dynamics and interaction of water vapor (clouds) and atmospheric chemistry (ozone) in the climate system. A part of this cooperation is this program of soundings during INDOEX, an international and multidisciplinary project with participation of internationally acknowledged experts in meteorology, atmospheric chemistry/physics, and oceanography.

References

Kley, D., P.J. Crutzen, H.G.J. Smit, H. Vömel, S. Oltmans, H. Grassl, V. Ramanathan. Observations of Near-Zero Ozone Levels Over the Convective Pacific: Effects on Air Chemistry. SCIENCE, 274, 230-233, 1996.

Kley, D., Tropospheric Chemistry and Transport, Science, 276, 1043-1045, 1997a.

Kley D., H. G. S. Smit, H. Vömel, H. Grassl, V. Ramanathan, P. S. Crutzen, S. F. Williams, S. Meywerk and S. Oltmans,.Tropospheric Water Vapour and Ozone Cross Sections in a Zonal Plane over the Central Equatoral Pacific. Quart. J. Roy. Met. Soc. 123, 2009-2040, 1997b.

Ramanathan, V. and W Collins, Thermodynamic regulation of ocean warming by cirrus clouds deduced from observations of the 1987 El Nino. Nature **351**, 27-31, 1991.

Smit, H.G.J., Sträter, W., Kley, D., Proffitt, M.H., The evaluation of ECC-ozone sondes under quasi flight conditions in the Environmental simulation chamber at Jülich, A contribution to subproject TOR , In: Transport and Transformation of Pollutants in the Troposphere, Proceedings of EUROTRAC Symposium '94, Garmisch-Partenkirchen, 11-15 April 1994 , P. Borrell, P.M. Borrell and W. Seiler Editors, SPB Academic Publishing, The Hague, The Netherland, pp. 349-353, 1994.

Informationen über INDOEX im Internet:

About the Center for Clouds, Chemistry and Climate (C^4)	http://www-c4.ucsd.edu/
About INDOEX	http://www-indoex.ucsd.edu/
About INDOEX-Shipcampaign on Research Vessel "Ronald Brown"	http://www.metolab3.umd.edu/~russ/INDOEX.ship.html

POSTER

Tropospheric Ozone as a Tracer for Large Scale Meridional Transport and Deep Convection

Dieter Kley and Herman G. J. Smit

Institut für Chemie der Belasteten Atmosphäre (ICG-2)
Forschungszentrum Jülich GmbH
D-52425 Jülich
Germany

Cumulonimbus Convection and Vertical Transport

Deep convection rapidly lifts surface air to the upper troposphere (up to 11-13 km without violation of the first law of thermodynamics). ´The cumulonimbus (Cb) transport has implications for:

- Upper tropospheric photochemistry
- Vertical distribution and redistribution of water vapor and clouds
- Radiation budget

Simultaneous ozone/water vapor soundings over tropical oceans (Atlantic, Pacific) revealed:

- very low ozone concentrations in the MBL and in the upper troposphere of the Intertropical Convergence Zone (ITCZ).
- slightly higher ozone concentrations in the middle troposphere.
- low ozone mixing ratios coincided with high relative humidity.

Ozone over Tropical Oceans

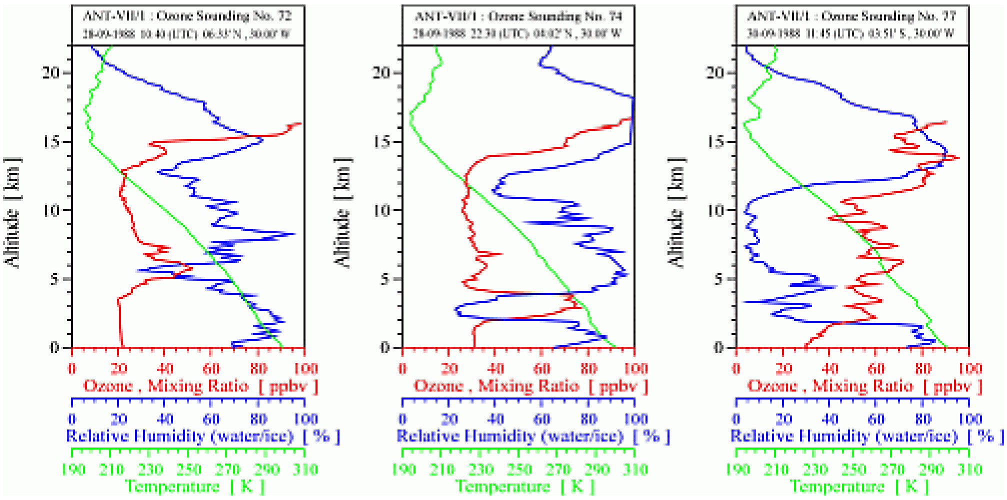
Low ozone concentration in the marine boundary layer (MBL), because of

- high water vapor concentration
- high UV flux
- low NO_x mixing ratio (<10pptv)[1]

Large ozone lifetime (>100days) and little ozone production in the free troposphere, because of

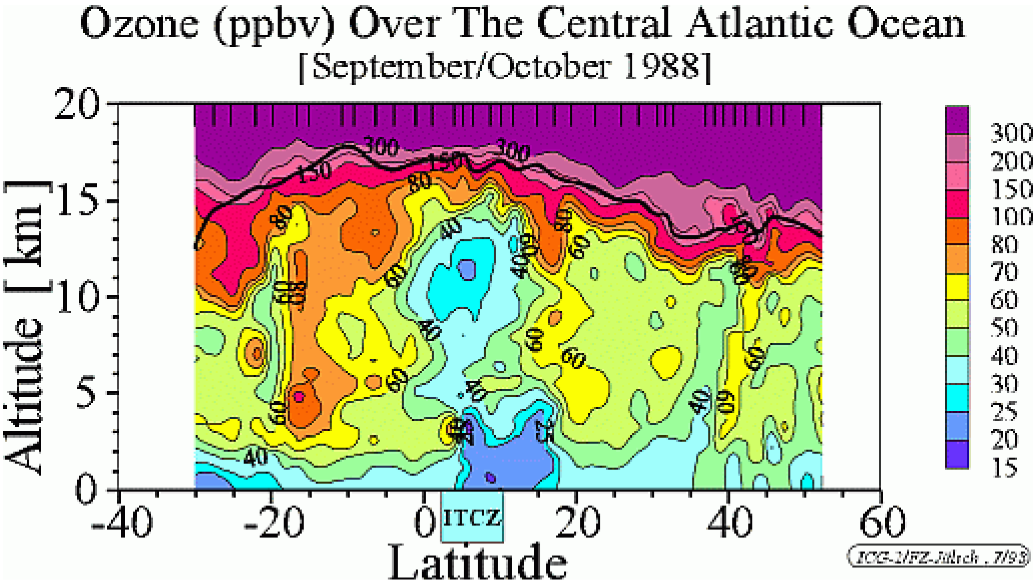
- low water vapor concentration
- relatively low NO_x concentration.

**[1]Liu, S.C., M. McFarland, D. Kley, O. Zafiriou and B. Huebert. Tropospheric NO_x and O_3 Budgets in the Equatorial Pacific.
J. Geophys. Res. 88, 1360-1368 (1983). See also Schultz et al., J. Geophys. Res. (in press)**



Examples of ozone/humidity soundings in the ITCZ region: Layers with enhanced ozone mixing ratios in the middle troposphere coincide with layers of low relative humidity suggesting inclined, downward sloping, transport of regions with higher ozone mixing ratios.

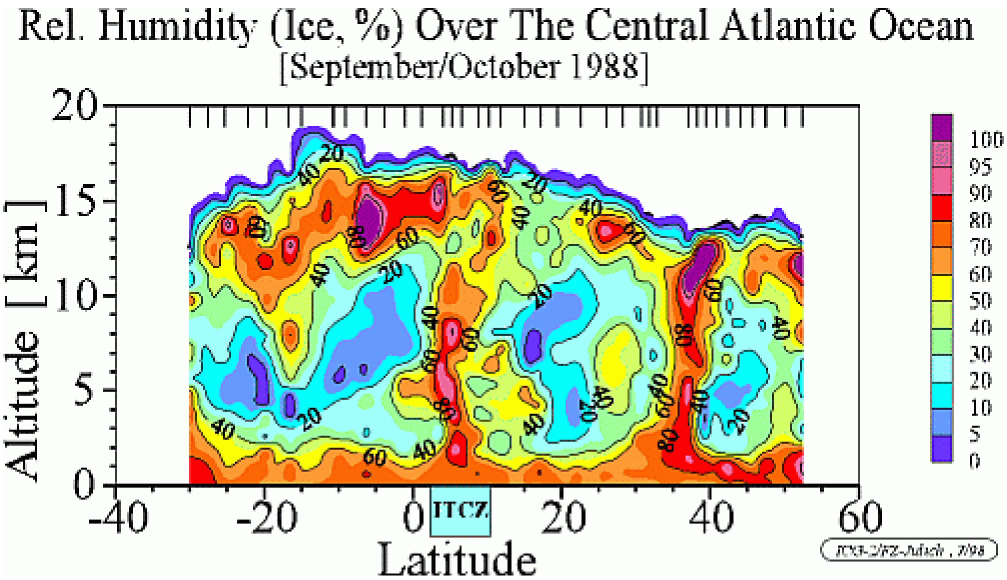
Ozone Cross Section



Meridional cross sections of ozone from shipboard soundings over the Central Atlantic mainly at 30°W. Linear interpolation of non-equidistant soundings (marks indicate latitudes of soundings). The black line in the upper troposphere indicates tropopause.

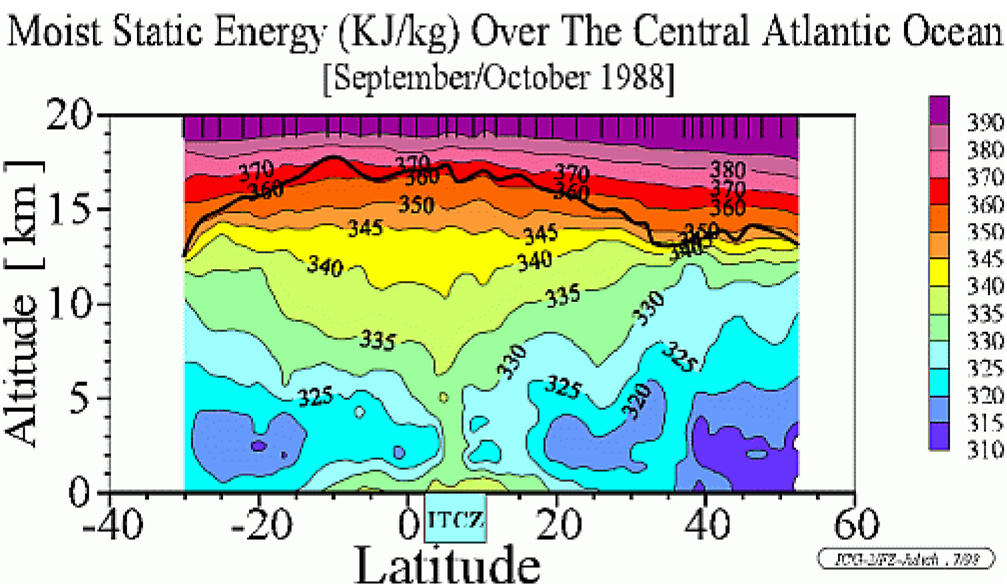
- Deep convection lifts ozone-deficient air. In the center of the deep convective region, upper tropospheric ozone mixing ratios are as low as the surface values.
- Downward transport occurs outside (north and south) of the ITCZ.
- Higher ozone value in the middle troposphere of the deep convective region indicate convergence and entrainment of air with an origin from outside of convective regions.

Soundings in the ITCZ region



- The troposphere above the ITCZ region is wet.
- To the north and south, the troposphere is dry.
- Complementarity of the ozone and humidity cross section which implies that ozone can be used as an "independent variable" for deep convection.
- Ozone as a tracer to draw conclusions on water vapor as a "dependent variable" of Cb convection.

Moist Static Energy Cross Section



- Cross section of moist static energy, Q (sum of potential energy, dry and latent heat content).
- Surface values of Q are high in the ITCZ region (335-340 kJ/kg).
- Minimum of Q (330-335 kJ/kg) in the middle troposphere over the ITCZ. Deep convection occurs in singular events which penetrate the minimum of Q in narrow "tubes" of constant energy.

Conclusions

- Transported air masses in the MBL loose ozone on their way to the ITCZ, where the ozone deficient air is lifted by Cb-convection.
- Active or recent deep convection marks its appearance in the upper tropical troposphere by very low ozone mixing ratio.

The use of ozone as diagnostic tool allows to conclude that:

- Air masses of upper tropospheric subtropical origin are transported to the tropics
- Large scale convergence takes place near 5 km (700 hPa, Q ≈330 kJ/kg), which entraines dry air into the convection.
- The cross section of moist static energy with its omnipresent minimum of ≈ 330 kJ/kg in the free troposphere above the ITCZ may be the result of mixing convective air (Q ≈345 kJ/kg) with air of lower Q of nontropical origin.

Outlook

- One of the striking and largely unexplained characteristics of the low latitude troposphere is the mid-troposphere minimum in the moist static energy, Q.
- This minimum creates an apparently stable Q gradient within the middle and upper tropopshere.
- Dry, ozone rich, subtropical air from the upper troposphere is advected to the tropics where it is entrained into convection.
- The mixing of dry with convective, high humidity, air lowers the thermodynamic moist static energy, thereby reducing the neutral buoyancy levels.

Key Question:

- Can the minimum of Q in the tropics be consistently explained by a circulation which, similar to the return flow of the Hadley cell, transports subtropical air to the middle troposphere (near 700 hPa) of the inner tropics?
- If so, could such a circulation excert a controlling influence on the extensity and intensity of deep convection?