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René Stübi

SONDEX / OZEX
Campaigns of dual ozonesondes flights: report on the data analysis

July 2002

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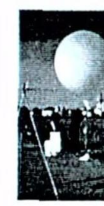
Abstract

In 1994, the swiss government has initiated a national project to develop the activities related to the "Global Atmospheric Watch" programme as defined by the World Meteorological Organization" (WMO). One of the component of this project concerns the activities related to ozone monitoring with the goal to improve and develop the measurements as well as to re-evaluate the existing data series.

The Payerne station which is one of the oldest station in the world measuring the atmospheric ozone profile, has taken the opportunity to develop its activities and notably to plan the change of the operational ozonesondes in 2002. Payerne and Hohenpeissenberg are indeed the last two stations with long term ozone sounding series performed with Brewer-Mast (BM) ozonesondes from the end of the sixties up to present days. Most of the other stations around the world presently measure ozone profiles with the Electrochemical Concentration Cells (ECC) ozonesondes which are recognised to have a better reproducibility than the BM. Besides this better reproducibility, the principles reasons to change sondes are the absence of developments and improvements of the BM manufacturing and the fact that maintaining the present quality of the BM measurements is more and more expensive (manpower, instruments, ...). However, the change of an apparatus dedicated to the atmospheric monitoring asked for a good preparation. The main problem being the appearance of a rupture in the measurements series which could impair the trend analysis of these data. Therefore numerous dual flights with two sondes (BM and ECC) have been launched between 1996 and 2001. The goal were to study and to compare the characteristics of each ozonesonde type in atmospheric conditions. The measured differences have then been analysed and the impact of a change of ozonesonde on the continuity of the Payerne long term sounding series has been evaluated.



These studies consist in three facets: first a short term campaign (SONDEX96) of dual flights was organised at Payerne together with the group of GSFC/NASA laboratory at Wallops Island, US. The second facet (OZEX) consists in a one year long comparison with a dual soundings every week incorporated in the operational duties of the Payerne station. The third facet concerns laboratory experiments were the ozonesondes are submitted to controlled conditions on the one hand, in the Payerne laboratory and on the second hand, during to international ozonesondes intercomparisons at the Jülich simulator (JOSIE/WMO campaigns).

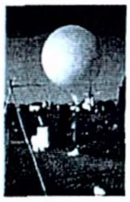
This publication presents the results of the dual flights of the two first facets (SONDEX96, OZEX) mentioned above. They appear as two distinct reports assembled in one brochure with a preamble section summarising the project and the results.

Résumé

En 1994, le gouvernement suisse a initialisé un projet national de développement des activités suisses dans le domaine de la "Veille Atmosphérique Globale" (VAG) tel qu'il a été défini par l'Organisation Météorologique Mondiale (OMM). Une des composantes de ce programme concernait les activités liées à l'ozone avec comme but l'amélioration et le développement des techniques de mesures ainsi que l'analyse des anciennes séries de données déjà existantes.

La station de Payerne qui est l'une des plus anciennes stations de mesures du profil d'ozone atmosphérique, a profite de ce projet pour développer ses activités notamment

en planifiant un changement de sondes opérationnelles pour l'année 2002. En effet, Payerne et Hohenpeissenberg sont deux stations qui possèdent de très longues séries de mesure d'ozone faite à l'aide de sondes de type BM (Brewer-Mast). La plupart des autres stations utilisent actuellement des sondes de type ECC (Electrochemical Concentration Cells) qui sont reconnues comme étant plus reproductibles que les sondes BM. Outre la meilleure reproductibilité, les principales raisons de ce changement sont l'absence de perspectives de développement et d'amélioration de la sonde BM de la part du fournisseur ainsi que le fait de maintenir la qualité des mesures faites avec les sondes BM implique un investissement financier et en personnel important. Cependant un changement d'instrument dans la cadre d'activités de surveillance de l'atmosphère nécessite une très bonne préparation. Le problème principal est la possible apparition d'une cassure dans la série de mesures de l'ozone qui pourrait rendre difficile, voire impossible l'analyse de l'évolution des ces données dans le temps. Ainsi de nombreux vols de comparaison avec deux sondes (BM et ECC) ont été effectués entre 1996 et 2002. Le but étant d'analyser et de comparer les caractéristiques de chacune d'elles dans les conditions atmosphériques réelles. Les différences constatées ont ensuite été analysées et l'impact d'un changement de sondes sur la série de mesures de Payerne a été évalué.



Cette étude a été réalisée en trois volets principaux: une première campagne de comparaison de sondes (SONDEX96) BM et ECC a été organisée durant trois semaines au printemps 1996 à Payerne conjointement avec le laboratoire GSFC/NASA de Wallops Island, USA. Le deuxième volet (OZEX) a consisté à faire un sondage de comparaison chaque semaine pendant une année et ceci dans le cadre du service opérationnel de Payerne. Dans le troisième volet, une série de tests de laboratoire dans des conditions contrôlées ont été réalisés, d'une part dans celui de Payerne et d'autre part, lors de deux campagnes internationales de comparaison de sondes dans le simulateur de Jülich en Allemagne (campagnes JOSIE sous l'égide de l'OMM).

Le présent rapport expose les résultats des sondages de comparaison des deux premiers volets (SONDEX96 et OZEX) mentionnés ci-dessus. Ils apparaissent sous forme de deux rapports distincts rassemblés dans la présente publication avec une introduction commune qui présente le projet et donne une synthèse des résultats.

Zusammenfassung

Im Jahre 1994 initiierte die schweizerische Regierung ein nationales Projekt zur Entwicklung von Aktivitäten im Bereich des "Globale Atmospheric Watch" (GAW) nach den Richtlinien der Weltmeteorologieorganisation (WMO). Ein Teil des Programms umfasste den Ozonbereich mit dem Ziel, bestehende Messverfahren zu verbessern und weiterzuentwickeln, sowie bereits vorliegende Messserien neu zu analysieren.

MeteoSchweiz Payerne (vormals Station Aérologique Payerne) gehört zu den ältesten Messstationen im Bereich der Vertikalprofile des atmosphärischen Ozons. Sie nutzte das GAW-Projekt zur Entwicklung ihrer Messaktivitäten; insbesondere ist vorgesehen, im Jahre 2002 einen Wechsel des Sondentyps vorzunehmen.

Payerne und Hohenpeissenberg sind beides Stationen mit Sondierungsreihen, die seit den Sechzigerjahren mit Brewer-Mast-Sonden (BM) durchgeführt werden. Die meisten benachbarten Stationen benützen Sonden des Typs ECC (Electrochemical Concentration Cell), welche stabilere Eigenschaften als die BM-Sonden aufweisen. Neben dieser

höheren Reproduzierbarkeit der Messresultate spricht für einen Sondenwechsel auch das Fehlen von Verbesserungen oder Weiterentwicklungen der BM-Sonde durch deren Herstellerfirma, ebenso der zunehmende - personelle wie finanzielle - Aufwand, den eine Beibehaltung des Qualitätsstandards dieses Instruments erforderte.

Allerdings verlangt ein Wechsel des Instrumententyps im Rahmen der Überwachung der Atmosphäre eine sehr gute Vorbereitung: Das Hauptproblem ist ein möglicher Bruch der Ozonmessreihe, welche für die Analyse von Langzeittrends verwendet wird. Deshalb wurde zwischen 1996 und 2002 eine grosse Anzahl von Parallelsondierungen mit je einer BM- und einer ECC-Sonde am Ballon durchgeführt. Das Ziel war, die Eigenschaften beider Sonden unter realen atmosphärischen Bedingungen zu analysieren und zu vergleichen, um den Einfluss der instrumentellen Unterschiede auf die langjährige Messreihe von Payerne anwenden zu können.

Diese Studie umfasste drei Teile: Eine erste Kampagne (SONDEX96) zum Vergleich der BM- und der ECC-Sonde wurde unter Mitarbeit einer Forschergruppe des GSFC/ NASA-Labors von Wallops Island (USA) während dreier Wochen im Frühjahr 1996 in Payerne durchgeführt. Die zweite Phase (OZEX) bestand in einer wöchentlichen Parallelsondierung während eines Jahres unter operationellen Bedingungen in Payerne. Der dritte Teil umfasste Testserien im Labor unter kontrollierten Bedingungen: einerseits wurden diverse Tests im Labor von Payerne realisiert, andererseits nahm MeteoSchweiz an zwei internationalen Kampagnen (JOSIE, unter der Aegide der WMO) zum Vergleich verschiedener Sondentypen im Atmosphärensimulator in Jülich (Deutschland) teil.

Der vorliegende Bericht präsentiert die Resultate der Vergleichsmessungen der obenerwähnten beiden ersten Phasen (SONDEX96 und OZEX) in zwei Teilen mit gemeinsamer Einführung.

Riassunto

Nel 1994, il governo svizzero iniziò un progetto nationale di sviluppo delle attività svizzere nel campo della "Vigiglia Atmosferica Globale" (VAG) come definito dall'Organizzazione Meteorologica Mondiale (OMM). Una delle componente di questo programma riguardava le attività legate a l'ozone avendo come scopo un miglioramento ed un sviluppo delle misure anziche un' analisi delle vecchie serie di misure.

La stazione di Payerne essendo l'una delle più anziane stazioni di misure del profilo di ozone atmosferico approffitò di questo progetto per sviluppare sua attività di misure notamente pianificando un cambiamento di sonde per l'anno 2002. Infatti, Payerne e Henenpeissenberg sono due stazioni aventi delle lunghe serie di misure di ozone fatte con le sonde di tipo BM (Brewer.Mast). La più granparte degli altri osservatori utilizzano attualemente sonde di tipo ECC (Electrochimical Concentration Cells) che sono riconosciute come le più riproducibile che le sonde BM. Oltre la miglior riproducibiltà, le principali ragioni di questo cambiamento sono l'assenza di prospettive di sviluppo e di miglioramento della sonda BM da parte del fornitore, e il fatto che mantenere della qualità di misure con le sonde BM coinvolge un investimento importante (umano, finanziario, etc.).

Tuttavia, un cambiamento d'instrumento nel quadro di attività di sorveglianza dell' atmosfera richiede una buonissima preparazione. Il problema principale è la possibile apparizione di una rottura nella serie di misure del ozone che potrebbe rendere difficile, perfino, impossibile le analisi dell'evoluzione delle misure. Perciò numerosi voli di confronto con le due sonde (BM e ECC) furono effettuate entro 1996 e 2002. Con lo scopo di analizare le caracteristiche di ogniuna nelle condizioni atmosferiche in modo di poterle paragonare. Facendo seguito alle differenze constatate fù valutato l'impatto di un cambiamento di sonde sul la serie di misure di Payerne.

Questo studio fù realizzato in tre fasi principali:

Una prima campagna di confronto di sonde (SONDEX96) BM e ECC fù organizzata durante tre settimane a primavera del 1996 a Payerne congiutamente con il laboratorio GSFC/NASA di Wallops Island USA. La seconda fase (OZEX) consistò nel fare un sondaggio di confronto ogni settimana durante un anno nel quadro del servizio operatorio di Payerne. La terza fase consistò in una serie di testi di laboratorio in condizione controllate: nel laboratorio di Payerne e al momento delle due campagne internazionali di confronto di sonde nel simulatore atmosferico di Julich in Germania (esperienza JOSIE sotto l'egida dell'OMM).

Il presente rapporto presenta i resultati dei sondaggi di confronto delle due prime fasi (SONDEX96 e OZEX). Infatti sono due rapporti distinti raccolti nella presente publicazione con un'introduzione comune.

Introduction to GAW-CH Program

In 1989, the World Meteorological Organization (WMO) has established the Global Atmosphere Watch (GAW) programme integrating a number of WMO's research and monitoring activities in the field of atmospheric environment (BAPMoN, GO3OS). The main objective of GAW is to " ... provide data and other information on the chemical composition and related physical characteristics of the atmosphere and their trends, required to improve understanding of the behaviour of the atmosphere ..."[1].

In 1994, the Swiss government decided to finance a six years national project, GAW-CH, to enhance the monitoring and calibration activities in Switzerland. The main emphasis was set on the developments of the Ozone (MeteoSwiss), the Radiation (MeteoSwiss) and the Aerosols (Paul Scherrer Institute) monitoring and on the building up of two world calibrations centres at WRC (World Radiation Centre, Davos) and EMPA (Swiss Federal Laboratory for Material Testing and Research, Zurich).

In the ozone sub-programme, different tasks have been defined, in particular:

- the development and improvement of ozone measuring techniques,
- the homogenization and reprocessing of old series,
- the development of an ozone microwave radiometer.

Within the first activity cited above, it has appeared that the long term ozone sounding series would be best assured in the future with the ozonesondes of type ECC (Electrochemical Concentration Cell) instead of type BM (Brewer-Mast) presently used. To properly prepare the transition from one sonde type to the other without endangering the long term series, it is required to study the characteristics of both ozonesondes in laboratory and in real atmosphere. Included in the GAW-CH programme, that preparation has consisted of the following main activities:

- SONDEX 1996: two weeks campaign of BM - ECC dual flights organized at Payerne in collaboration with GSFC/NASA laboratory at Wallops Island, US,
- OZEX 1998 - 1999: one year of weekly BM - ECC dual flights incorporated in operational service of the Payerne station,
- JOSIE 1996: two weeks campaign at the Jülich simulator with BM ozonesondes,
- JOSIE 1999: similar to the 1996 campaign but with ECC ozonesondes,
- laboratory tests with ECC and BM ozonesondes in Payerne.

These various experiments allowed to develop a large dataset that was used to characterise, study and explain the differences between the BM and ECC ozonesondes. In particular, the dual flights campaigns give valuable and unique information on the behaviour of the sondes in the same environment. They allow to accumulate enough information and confidence to authorize the switch from BM to ECC ozonesondes.

This publication gather the SONDEX96 and the OZEX individual reports as these two experiments were independently analysed.

The analysis of the JOSIE 1996 campaigns are reported in WMO reports[2]. The laboratory test results are documented in the report by Levrat and Hoegger, 2000[3].

1. www.wmo.ch/index-en.html
2. Global Atmosphere Watch - GAW report No. 130 / WMO - TD 926
3. G. Levrat and B. Hoegger, Comportement des capteurs d'ozones BM et ECC dans un environnement idéal et ambiant", *Internal report*, MeteoSwiss, 2000.

Outline of ozone project

In situ atmospheric ozone measurements represent a challenging task in particular in regard to the:

- very low ozone partial pressure which requires an instrument with nanobar resolution,
- limited payload which cannot exceed the commercially available balloons lift power (~ 1 kg),
- large ozone variability with altitude asked for fast response instruments,
- low stratospheric temperature which requests a good thermal insulation of the sonde.

The ozonesondes which respond to the above requirement have been developed in the late sixties and are based on the chemical reaction of a potassium iodine (KI) diluted solution with atmospheric ozone molecules sampled outside the ozonesonde box by a small pump. The measured ozone partial pressure is instantaneously radio transmitted to the ground station. Because of the high reactivity of the ozone, any residual substance will destroy the ozone before detection by the sonde. Therefore a very meticulous approach in the preparation of the ozonesondes is required.

The Payerne sounding series started in 1968 using BM ozonesondes without interruption up to present time. In the earlier years, the manual analysis of paper chart recordings and simplified procedures in the preparation of the sondes were the major limitations to the measurements precision and reproducibility. With the progress of the sounding technique and the introduction of the digital recording, but also through the introduction of a standardized and automated operation in the pre-flight preparation of the ozonesondes, the limits of the measurement technique have been pushed one step further. The sounding accuracy limitations have now moved towards the manufacturing aspects of the ozonesondes like the quality of the material and the fabrication norms. In this perspective, the BM are more limited than the ECC ozonesondes. They are also recognized as having a better reproducibility than the BM ozonesondes probably benefiting of a simpler fabrication process. Keeping the present BM measurements quality ask for important costs (financial, manpower) and the future appears uncertain. These elements imply that a change of the ozonesonde type from BM to ECC for the operational soundings in Payerne has been planned for year 2002.

However, the importance of the continuity of old ozone sounding series is obvious for the GAW programme and the climate monitoring. The analysis of the temporal evolution of the ozone at various altitudes is a key aspect for the understanding of the ozone evolution. For example, the full tropospheric part of the ozone profile is uniquely measured by ozonesondes in comparison to other system like satellites and remote sensing systems. In this respect, the continuity of the in situ measurements has to be assured.

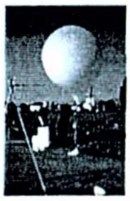
All these constrains asked for an intensive comparison program between the present operational BM ozonesonde and the envisaged future ECC ozonesonde to assure a smooth transition.

Two aspects have to be considered, the first one concerns the manufacturing of the ozonesonde as already mentioned while the second concerns the data processing. In principle, the manufacturing of the sonde determines the first one and no modification are performed afterwards. However, during the preparation procedure the main parts are dismantled and reassembled after cleaning. Some impurities or imperfections can be removed in this process and quality criteria have to be satisfied. Secondly regarding the processing of the data, major differences exist between the two sondes which are somehow artificial and have no reason to persist. Therefore, a more uniform approach in the data processing is performed and discussed in details in these SONDEX96 and OZEX reports.

Summary of the results

The first campaign, named SONDEX96, has been conducted between April and May 1996. Over a two weeks period, 33 dual flights were launched with up to 4 flights released the same day.

The second study, named OZEX, has been coordinated with the operational sounding activity of the Payerne station. Over the period of March 1998 to June 1999, dual flights were released every week with the Wednesday noon aerological sounding. The study has continued with a lower frequency of one dual flight per month after June 1999. The OZEX study has allowed to constitute a set of about eighty dual flights appropriate for statistical analysis.



The results based on these dual flights present systematic differences illustrated in fig. 1 below. The relative difference profiles between the BM and the ECC ozonesondes measurements show a good consistency between the two studies. Significant differences between the two ozonesondes are located at the tropopause level around 10 km and at the middle stratosphere above 28 km. At the ozone layer altitude (20 - 24 km) in presence of high ozone concentration, the two ozonesondes agree well. The horizontal lines, representing $\pm\sigma$, denote the large fluctuations around the mean differences. If the tropospheric differences are not significant compared to the variability of the measurements, the middle stratosphere (30 km) differences are clearly unidentifiable as a rupture in the time series. The results presented in fig.1 are achieved with the conventional

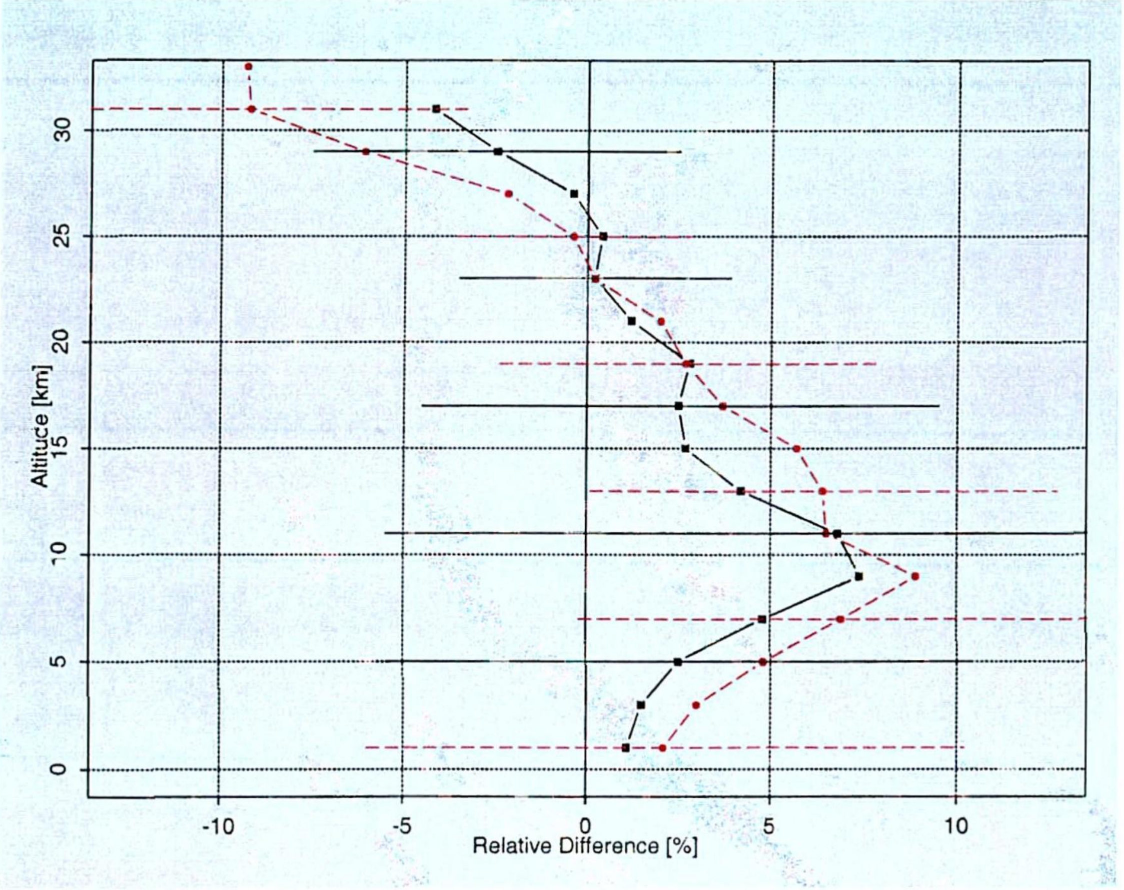


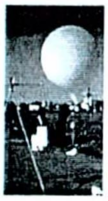
Fig. 1: Difference profiles between BM and ECC ozonesondes relative to ECC determined in the SONDEX96 (red dashed line) and OZEX (black solid line) experiments. Horizontal segments represent $\pm\sigma$.

data processing for the ECC ozonesondes and with the standard procedure, as defined by WMO, for the BM ozonesondes.

The results of Fig. 1 depend on the following factors which enter the calculation of the ozone partial pressure from the raw current measured in flight by the sondes:

- Correction for the loss of pump efficiency at low pressure (high altitude),
- Temperature of the air when passing through the pump,
- Removal of back-ground residual current in the elector-chemical cell,
- scaling of the total ozone integrated from the profile to independent measurement from Dobson instrument.

The difficulty associated with the analysis of the impact of these items on the calculated ozone is firstly, the compensating effects when they are applied together and secondly, the non-linear effect of the scaling which redistributes the ozone along the ozone profile. In the fig.2 below, relative difference profiles for the OZEX dataset is shown for two alternative BM data processing, the black line being the same as in fig. 1.



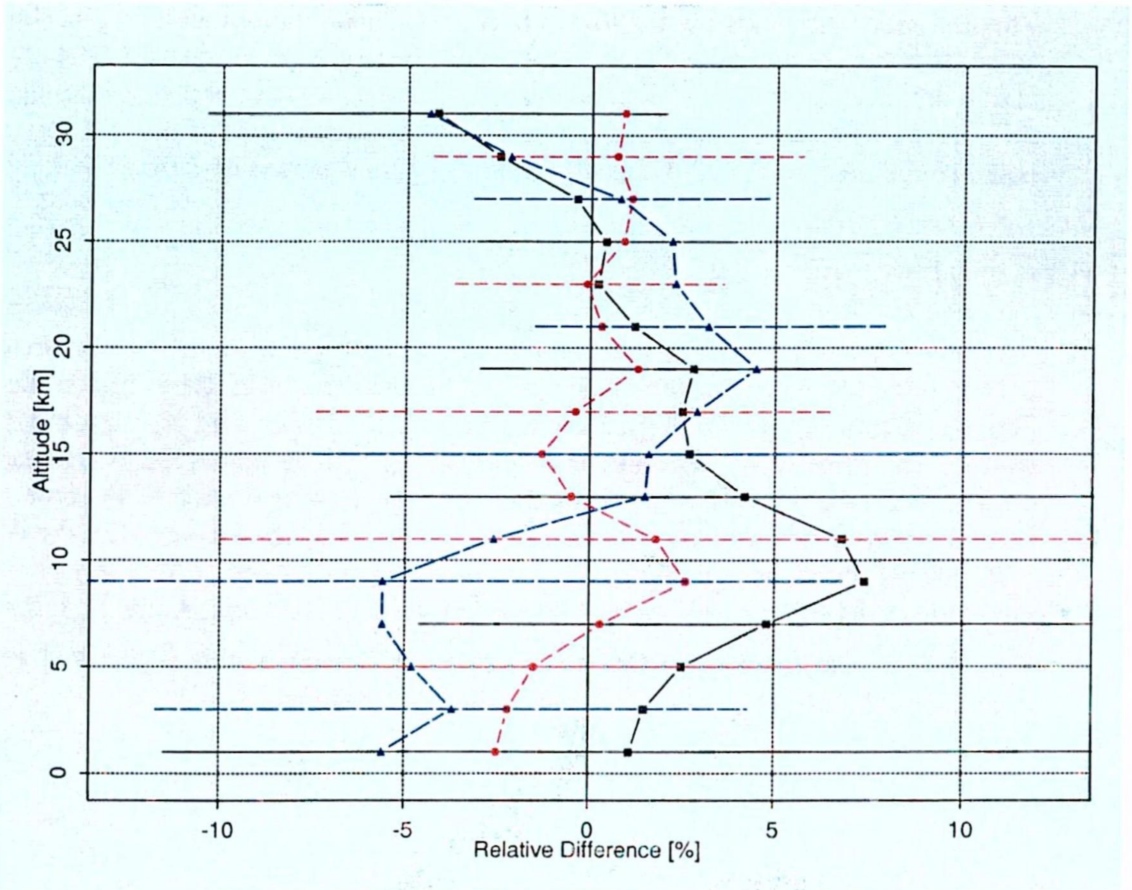


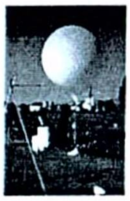
Fig. 2: Difference profiles between BM and ECC ozonesondes relative to ECC determined in the OZEX study. Compared to the full line in fig. 1, changes in the data processing of the BM have been introduced, the raw data being the same. For the legend, see text.

The blue line is obtained when the back-ground signal is taken into account for the BM sondes (see §4.2 fig. 5 of the OZEX report). The red line illustrates a different treatment for the pump efficiency correction and the pump temperature in the BM data processing (see §4.4 fig. 8 of the OZEX report). The comparison of the difference profile in fig. 2 demonstrates the impact and importance of the data processing in the comparison of the two ozonesondes.

These elements are extensively discussed in this report since there is a need for a consensus in the ozonesonde users community in regard to the data processing. The present studies aim to show the consequences of various options and is a contribution to the debate. The definite statement on the comparability of BM and ECC ozonesondes can only be expressed if the data processing steps are clearly established.

The conclusion of these experiments is that two types of processing will be undertaken to homogenize the transition from BM to ECC ozonesondes:

- The BM SOP data processing is strictly applied and the final ozone values have to be corrected according to a transfer profile as illustrated in fig 1.
- The BM SOP is not applied and a data treatment similar to the one applied to ECC sondes is favourable. This requires to determine an adequate mean pump temperature profile and an adequate back-ground signal. If this procedure is successful, no further adjustment should be necessary on the final ozone values.



The first procedure above will allow to keep a BM data without affecting its characteristics since the series on pressure levels will just be shifted by a constant. The drawback is that an blind correction is applied without physical basis to explained the measured differences. The second procedure can affect the characteristics of the BM series if the new parameters introduced in the data processing have varied with time.

Acknowledgments

We are very grateful to the continuous efforts of many people in order to obtain reliable ozone sounding measurements in Switzerland since the end of 1966, first at the Swiss Federal Institute of Technology, Zürich (Prof. H. U. Dütsch and co-workers), then at the Federal office of meteorology and climatology (Dr. P. Viatte, Dr. B. Hoegger and co-workers). We acknowledge all members of the technical staff of Payerne for the careful performance of the pre-launch procedures and of the ascents with the BM and ECC ozonesondes, as well as for the data handling (G. Levrat, J-M. Clerc, J-M. Cornuz, F. Joye, M. Limat, J-C. Aubort, B. Henchoz, P-A. Mettraux, A. Pittet, J. Rapin).

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MeteoSwiss

SONDEX96

Report on Data Processing

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A Joint Experiment of NASA and MeteoSwiss

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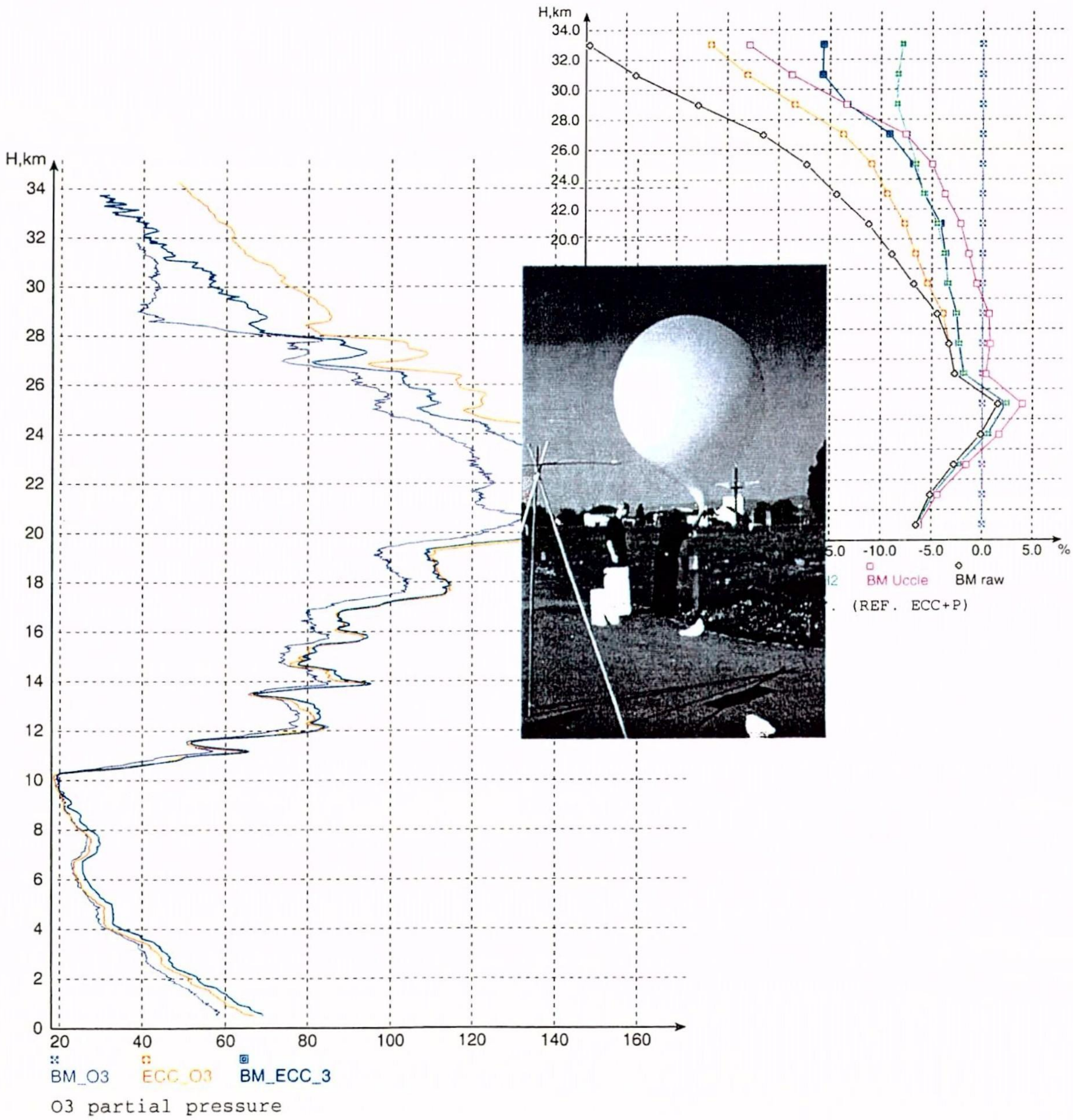

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List of symbols and abbreviations

BM	**B**rewer-**M**ast ozonesonde
BMpECC	BM ozonesonde with an ECC teflon pump
$E(z,T_p(z))$	Pump efficiency correction including the pump temperature dependence
ECC	**E**lectrochemical **C**oncentration **C**ell ozonesonde
ENSCI	ENSCI Corporation, provider of ECC ozonesondes
f_c	Scaling factor
GAW	**G**lobal **A**tmospheric **W**atch, WMO program
GSFC	NASA **G**oddard **S**pace and **F**light **C**entre
H1, H2	BM pump efficiency correction from Steinbrecht et al., 1997
i_{b2}	Back-ground current of an ECC ozonesonde
JOSIE	**J**ülich **O**zone **S**ondes **I**ntercomparison **E**xperiment
K86	ECC pump efficiency correction from Komhyr et al.,1986
K94	ECC pump efficiency correction from Komhyr et al.,1994
MeteoSwiss	Swiss Federal Office for Meteorology and Climatology
MOHp	**M**eteorological **O**bservatory **H**ohen**p**eissenberg, DWD
NASA	**N**ational **A**eronautical and **S**pace **A**gency
offset	BM residual ozone extrapolated from laboratory calibration
OP	**O**perating **P**rocedure
pos0	BM residual ozone measured in laboratory calibration
SONDEX96	Campaign of parallel BM - ECC soundings at Payerne
SOP	**S**tandard **O**perating **P**rocedure
SPC	**S**cience **P**ump **C**ompany, provider of ECC ozonesondes
$T_p(z)$	Pump temperature profile
WMO	**W**orld **M**eteorological **O**rganisation

List of labels in figures

...+D	Scaling of ozone profile with Dobson column is applied
...+P-H1	H1 pump efficiency correction is used
...+P-H2	H2 pump efficiency correction is used
...+P or +P-Std	Standard pump efficiency correction is used
...+P-K86	Pump efficiency correction from Komhyr, 1986 is used
...+P-K94	Pump efficiency correction from Komhyr et al., 1994 is used
...+T_p(=280K)	Pump temperature assumed to be constant at 280 K
...+$T_p(z)$	Actual or mean pump temperature profile
...+offset	Residual ozone correction applied using offset
...+pos0	Residual ozone correction applied using pos0
UCCLE	Pump efficiency and Dobson scaling according to Uccle procedure
SOP	Data processed according to **S**tandard **O**perating **P**rocedure for BM
$E(z,T_p(z))$	Pump efficiency correction dependant on altitude and pump temperature

List of figures

1. Introduction

The ozonesondes, developed in the late fifties, are very suitable for in situ atmospheric measurements. Two major design for these sondes are presently in use: the Brewer-Mast (BM) type and the Electrochemical Concentration Cell (ECC) sondes type, the second one dominates largely the market. The coexistence of these instruments in different monitoring networks and in campaigns asked for a detailed study of their respective characteristics. Payerne and Hohenpeissenberg are last two stations with long term ozone sounding series performed with BM ozonesondes. The Uccle station long term record has also been recorded with a BM ozonesonde up to 1997 and with an ECC afterwards. A change of sonde type is also anticipated in Payerne due mainly to the fact that keeping the quality of the BM measurements is not assured for the long term and no developments and improvements of BM are expected. Many experiments have shown that the BM ozonesondes are also less reproducible than ECC sondes. The best comparison method is the dual flight experiments where two sondes are attached to the same balloon.

This report presents the results of a short term campaign of dual flights, called SONDEX96, organised at Payerne together with the group of GSFC/NASA laboratory at Wallops Island, US. The goals of SONDEX96 were firstly to compare the performances of the BM and ECC ozonesondes and their differences and secondly, to evaluate which part of the differences could be explained by alternate data processing schemes.

As discussed in details in this report, the major components in the data treatment are:

- The loss of pump efficiency at high altitude (low pressure),
- The pump temperature necessary to convert volume flow to mass flow,
- The background current which is present even if the ozonesonde samples pure air,
- The scaling to Dobson total ozone necessary to compensate uncontrolled ozone loss

In general, the influence of the first three parameters on the measured ozone is confined to parts of the profiles. However, the scaling to the Dobson column imposes the conservation of the total ozone amount. It causes therefore, a redistribution of those local changes of ozone on the entire profile.

1.1 Structure of the Report

In section 2, a description of the SONDEX96 campaign is presented. In section 3, the different steps of the data processing are described separately for the BM and the ECC devices. It allows to quantify the different factors that affect the final ozone values for each ozonesonde type. In section 4, the analysis of the differences observed between the ozonesondes types is presented and analysed taking into account the results of section 3.

2. SONDEX96 campaign

2.1 Ozonesonde types

SONDEX96 is a MeteoSwiss and Goddard Space Flight Centre (GSFC) joint field experiment to investigate the differences between the two ozonesondes types. The campaign of multiple-sondes flights was organized by MeteoSwiss at Payerne, Switzerland, from April 26 to May 10, 1996. Two types of Electro-chemical Concentration Cell (ECC) and two types of Brewer-Mast (BM) ozonesondes have been used:

- ENSCI, ECC sondes produced by EN-SCI, Corp., US
- SPC, ECC sondes produced by Science Pump Corp., US
- BM from Mast-Keystone Comp., US
- BMpECC, a modified BM to incorporate a teflon pump like in the ECC ozonesonde

A description of the ozonesondes types can be found in Levrat and Hoegger (1999). The two ECC sondes are basically the same but they have been produced by two different manufacturers. The BMpECC instrument was tested to establish whether an improvement of the BM pumping system were possible. Unfortunately, the BMpECC hybrid system has given uncommun results, being neither close to a BM nor to an ECC behavior. A technical misfunctioning is probably at the origin of the problem. These data are therefore not included in the present analysis.

2.2 Preparation procedures

The BM sondes were prepared and handled by the MeteoSwiss personnel and the ECC sondes by the GSFC staff. A crucial part of the BM ozone sounding is the preparation of the sonde. This procedure has to be meticulously followed. The MeteoSwiss team uses an Operating Procedure (OP) elaborated at Payerne for the BM preparation which differs from the Standard OP (SOP) (WMO, 1987) on minor points. Mainly, the handling of dangerous chemical solution have been avoided in the cleaning process and a laboratory calibration of the sondes with a reference spectrophotometer (Monitor Lab type ML-9810) is performed prior to the flight.

The GSFC team used an OP specifically developed for their ECC instruments. In particular, individual pump efficiency calibration and sonde quality control are unique procedures used at GFSC Wallops Island site. A reference photometer (Dasibi Type 1008-PC) is used for the ECC sensor preflight calibration in laboratory.

2.3 Field procedure

Table 1 shows the day and times of all the SONDEX96 soundings. By the end of the two weeks campaign, 33 balloons had been released out of which 29 are considered as valid for statistical analysis. Out of these 29 flights, 9 flights included ENSCI sondes and 20 flights included SPC sondes.

The balloons were all released with three different ozonesondes attached underneath and disposed on the same boom (~2 m long) as sketched below (fig. 1):

- flights numbers 1 to 10 were in the order 1-2-3, except flight number 2 (1-3-2)
- flights numbers 11 to 33 were in the order 2-1-3

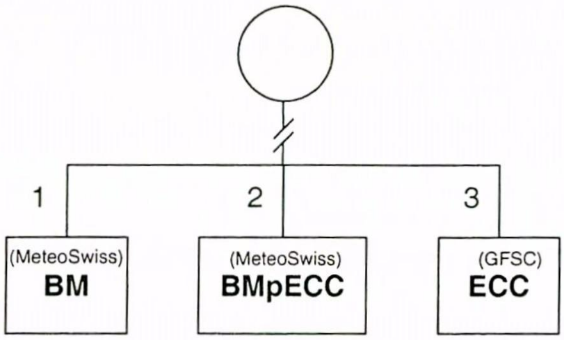


Fig. 1: Disposition of the ozonesondes under the balloon

Date/Time	09 UTC	12 UTC	15 UTC	18 UTC	21 UTC
Fr 26.04.96			(01) - S		
Mo 29.04.96		02 - S	03 - S		
Tu 30.04.96	04 - S		05 - S	06 - S	
We 01.05.96	07 - S	08 - S	(9) - E		
Th 02.05.96	10 - S	(11) - S	12 - S	(13) - S	14 - S
Fr 03.05.96	15 - S	16 - E	17 - S		
Mo 05.05.96	18 - S	19 - S	20 - S		
Tu 07.05.96	21 - S	22 - S	23 - E	24 - E	
We 08.05.96	25 - S	26 - E			
Th 09.05.96	27 - S	28 - E	29 - E	30 - E	
Fr 10.05.96	31 - E	32 - S	33 - E		

Table 1: *Flights number sorted according to date and time (the flight No into brackets are not used for statistical analysis). "S" corresponds to SPC type 6A sondes while "E" corresponds to ENSCI type Z sondes used by the GFSC team.*

The schedule imposed an intensive activity far beyond the normal operational conditions and therefore some preparation procedures of the BM could have suffered from this stress. The same appreciation could be done for the GFSC team which were working in an unfamiliar environment for the preparation of the ECC ozonesondes which are however much less sensitive to pre-flight conditioning.

2.4 Total ozone column

The total ozone column is measured operationally with different spectrophotometers at Arosa, an Alpine site (1850 m amsl) located about 200 km eastward of Payerne. The reference value for Payerne is the daily average measured with the Dobson #101. In fig. 2, the time series of the total ozone for the period of SONDEX96 is illustrated with indication of the campaign's day by arrow. The averaged value was about 350 DU during the campaign but it changed by more than 80 DU between the 3rd and 4th of May.

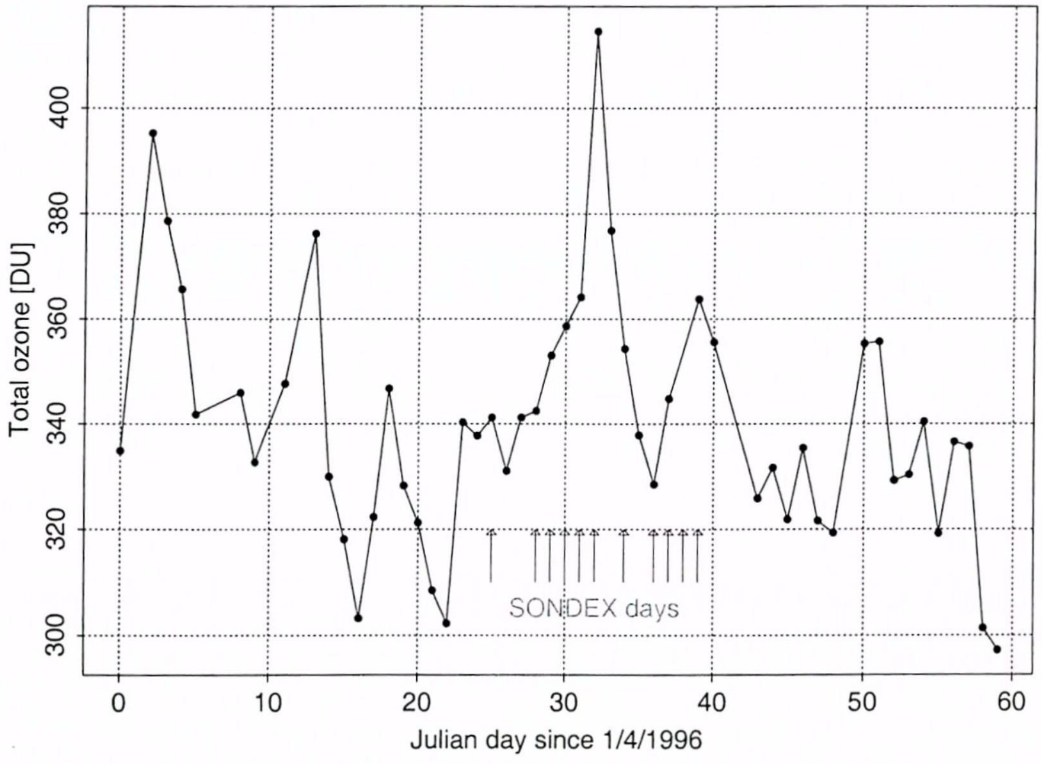


Fig. 2: Time series of the total ozone column for the SONDEX96 period.

2.5 Meteorological conditions

During the campaign the general meteorological conditions were characterised by unstable weather with sunny and rainy spells. The main meteorological parameters as well as the ozone at ground level are reproduced in fig. 3. The temperature was generally between 5-20°C during the day. It rained several times and some balloons (flights No 9-12-24) were launched in windy conditions.

The tropopause level was between 10 and 11 km (224-265 hPa), except for Friday 3 May (flights 15-16-17) when it came down to 8 km (363 hPa).

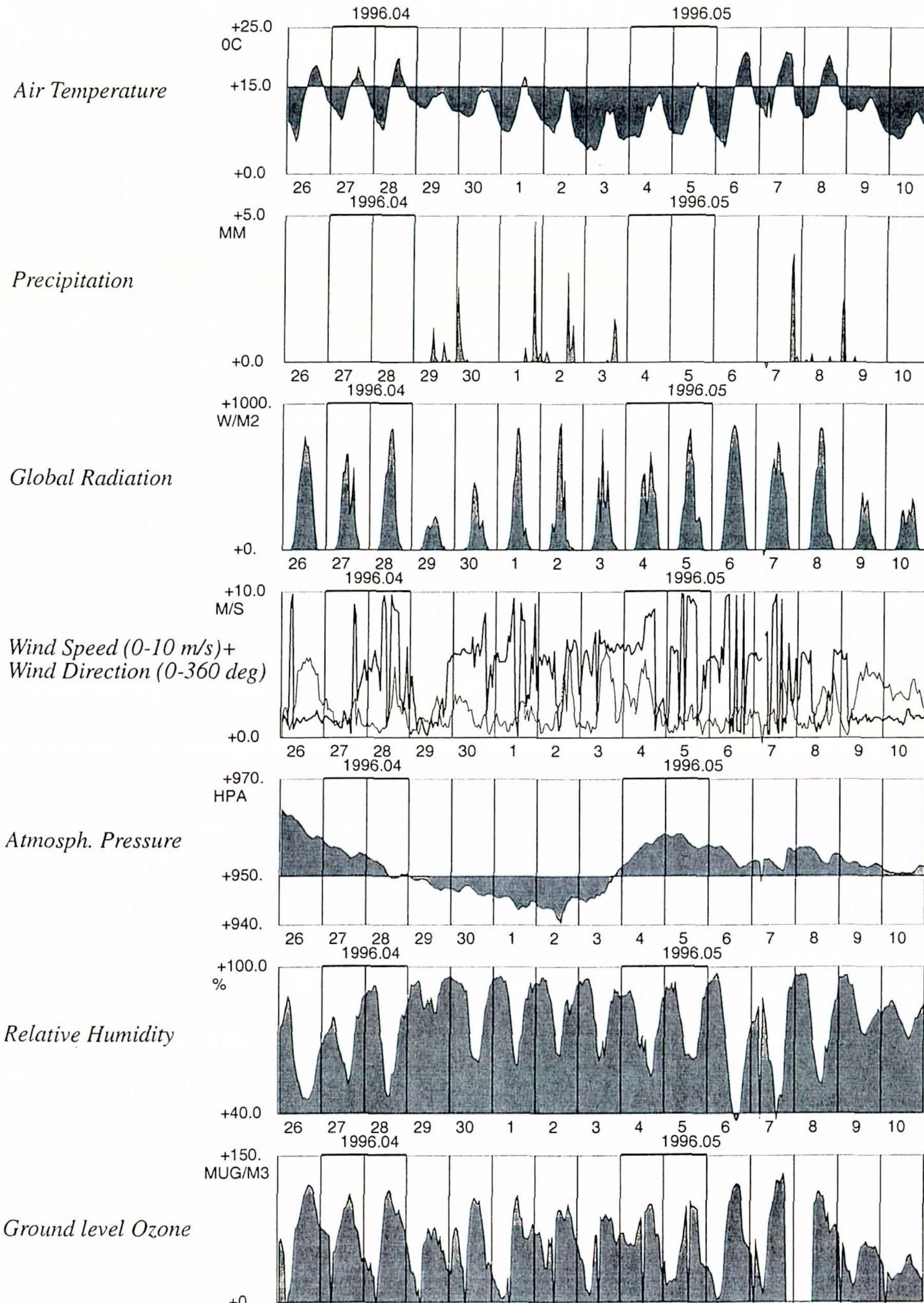


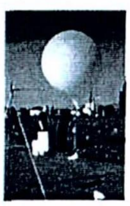
Fig. 3: Evolution of the meteorological parameters for the period 26.04.96 - 10.05.96.

3. Data processing

The physical quantity measured by the both BM and ECC sensor is the current. This current measured in the outer circuit is the result of the chemical reaction between the ozone molecules and the KI molecules diluted in the aqueous solution (WMO, 1987).

The general form of the equation relating the ozone partial pressure P_{O3}[nbar] to the measured current i [μA] is:

$$P_{O_3}(z) = cst \cdot (i(z) - i_b) \cdot F \cdot T_p(z) \cdot E(z) \qquad (1)$$



where:
- $cst = R/(2 \cdot e \cdot N_A) = 0,00431$ [nbar · dl / K · μA · s]
- R is the universal gas constant, e the elementary charge, N_A Avogadro's Number
- i(z) is the current [μA] measured at the altitude z
- i_b is the background current [μA]
- F is the flowrate expressed as the time to pump 100 ml of air [s/dl]
- $T_p(z)$ is the pump temperature[K] at the altitude z
- E(z) is the pump efficiency correction at the altitude z.

The terms i(z), $T_p(z)$ and E(z) depend on the altitude z of the sonde while i_b is considered constant. Instead of the altitude, pressure is also commonly used as vertical coordinate since it is the elevation parameter measured by aerological sondes. The two scales are interchangeable as long as air temperature is recorded too.

The ozone pressure, calculated with equ. 1 for both sondes, depends on the type of data processing used. The various terms of equ. 1 as well as the way they are treated by the users, are described in the following sections of this report and summarized in table 2.

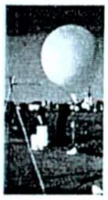
PARAMETERS	BM	ECC
Pump efficiency correction E(z)	1. Standard curve (Komhyr 65) 2. MOHp[a] (H1+H2) curves 3. Uccle procedure	1. Komhyr, 1986 2. Komhyr, 1994 3. Measured for each sondes
Pump temperature $T_p(z)$	1. Constant: 300K (MOHp) 2. Constant: 280K (MeteoSwiss)	1. Measured in each flight
Residual background current i_b	NO Correction ($i_b = 0$)	Correction by a measured residual current (constant) i_b
Dobson scaling	Applied	**Not** applied

Table 2: Table of the practices and parameters for ECC and BM data processing.

a. Meteorological Observatory Hohenpeissenberg, DWD Germany (Steinbrecht et al, 1998)

3.1 Dobson scaling

To complete the ozonesonde observations as calculated with equ. 1, the total ozone amount is integrated from the surface to the last point of the sounding. The residual ozone column above that point is obtained from this last point assuming a constant mixing ratio between the ozone partial pressure and air pressure. Adding these two contributions gives the ozonesonde integrated ozone. This quantity is compared to the total ozone measured with the Dobson spectrophotometer and a scaling factor is calculated to correct the ozonesondes data. This procedure guarantees that the ozonesonde total amount of ozone is correct but it is based on two questionable hypothesis: first, the constant mixing ratio of ozone relative to air pressure above balloon burst and, second, the deficit or excess of ozone recorded by the ozonesonde is proportional to the actual ozone amount. The first hypothesis is certainly a crude approximation of the reality measured by different systems (LIDAR, μ-wave, satellites,...) but, in the altitude range of the balloon burst, the error on the column is of the order of a few percent. The second hypothesis is more difficult to check. The experimental results show that BM ozonesondes present a deficit of ozone with a scaling factor around 1.10 while the ECC ozonesondes have an apparent excess of ozone with a scaling factor slightly lower than one. Furthermore, actual atmospheric temperatures are ignored in the retrieval algorithm of total ozone.



3.2 Pump efficiency E(z)

The efficiency of the pump of the ozonesonde decreases with altitude when the pressure decreases. Therefore corrections, reported in terms of pressure, are used to compensate this effect. These correction profiles are difficult to measure accurately and specific for each sonde type. Unfortunately, the currently used corrections also differ from station to station for the same type of sondes. The absence of an SOP for ECC sondes is partly due to the present disagreement on the appropriate pump correction profile.

3.2.1 BM standard correction profile

For BM sondes, a standard correction profile which corresponds to the table proposed by Komhyr and Harris (1965), is recommended in the BM SOP published by the WMO (1987). This correction profile was obtained from a set of five pumps tested in a vacuum chamber at laboratory conditions. This standard curve is in use for **operational** measurements at Payerne and at Hohenpeissenberg.

Recent laboratory measurements performed at GSFC according to the Torres's method (Torres, 1985) have confirmed this standard correction to within a few percent. Two pumps have been used, each being measured four times. In fig. 4, the GSFC and the standard correction are presented. The error bars correspond to $\pm\sigma$. The GSFC measurements are interpolated linearly between 1000 hPa and 60 hPa, so the difference in that pressure range is artificial.

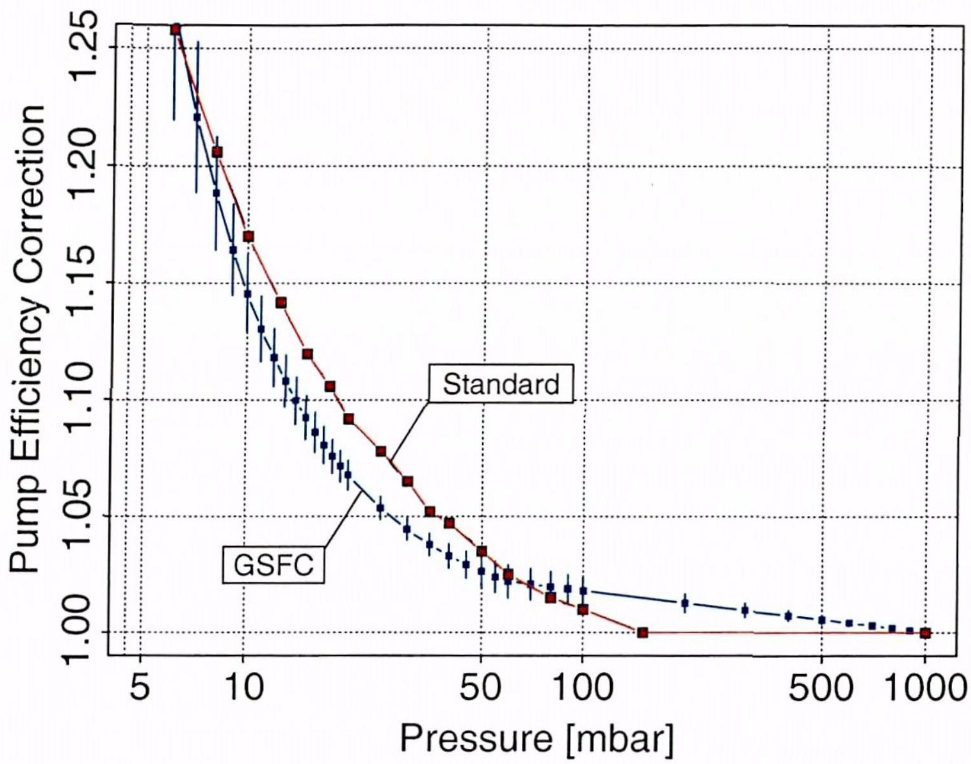


Fig. 4: Pump efficiency correction curves for the BM sondes. Large red symbols are the results of Komhyr and Harris (1965) and the blue symbols are the results from GSFC laboratory measurements. Error bars are $\pm\sigma$.

3.2.2 BM correction profile from Hohenpeissenberg (MOHp)

At the MOHp, two pump correction profiles were determined. One is the result of measurements in a vacuum chamber (H1), the other (H2) is derived from intercomparisons between BM sondes and other ozone profiling instruments: Hohenpeissenberg lidar, overpassing satellites (SAGE II, HALOE) and WMO ozonesondes intercompariaons at Vanskoy, Canada in 1991 (Steinbrecht et al., 1998). Postulating that the difference between the other instruments and the BM sondes is due its pump efficiency decrease, a new correction is calculated from the mean differences profile. However, for the operational soundings at MOHp, the standard correction is still in use.

In fig. 5, MOHp correction curves are plotted together with the standard correction. H1 and H2 are similar at high pressure but they differ as pressure decreases. The H1 correction is about 50% higher then the standard correction. The H2 correction adds an extra 5-8% below 20hPa compared to H1 which corresponds to more than 30 % total correction below 10 hPa.

The comparison of fig. 4 and fig. 5 reveals a discrepancy between the GSFC and MOHp correction profiles determined in two laboratories.

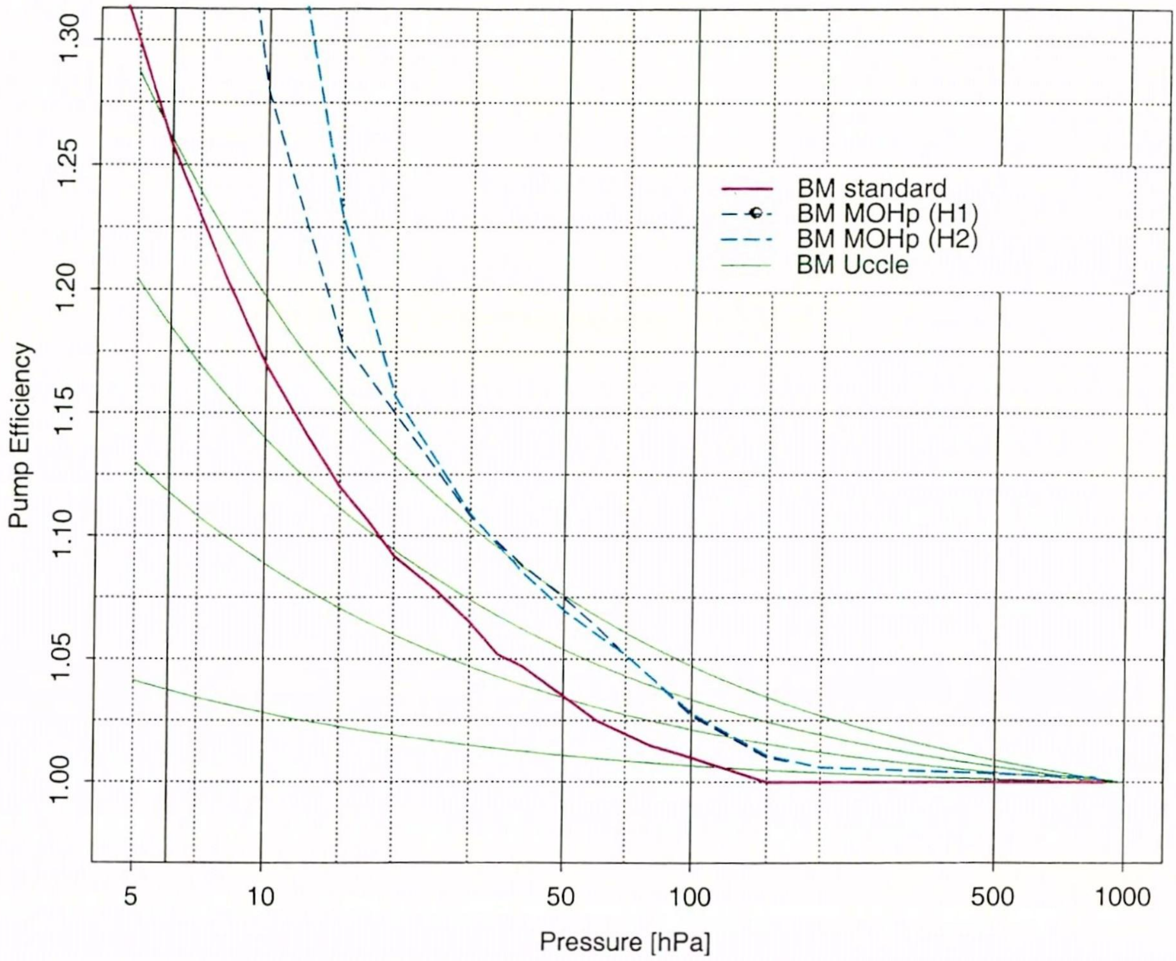


Fig. 5: Comparison of four different BM pump efficiency correction profiles. The Uccle corrections are illustrated with b values (see equ. 2) of 0.1 (bottom curve), 0.25, 0.5 and 1.0 (top curve).

3.2.3 BM correction profile from Uccle

In Uccle (Belgium station), BM sondes were used until March 1997. In the last years of BM activity and for some of the sondes, individual pump efficiency correction was determined in the laboratory before launch. The data points are adjusted to the following parametric equation (De Backer et al., 1998):

$$E(p) = c_0 \cdot \frac{1 + \sqrt{\frac{b}{p}}}{1 + \sqrt{\frac{b}{p_0}}} \tag{2}$$

where
- p is the atmospheric pressure (~1000 hPa < p < ~5 hPa)
- c_0 is the ozone calibration value at P_{O3}=75 nbar specified in the BM SOP

- p_0 is the atmospheric pressure at the ground
- b is an adjustable parameter specific for each pump

In absence of laboratory determination of the parameter b, it is adjusted so that the integrated ozone from the sonde profile matches the ozone column measured with a co-located Dobson spectrophotometer (see §3.1) (De Backer et al., 1996, 1999). This Uccle correction, represented in fig. 5 for four typical values of b: 0.1, 0.25, 0.5 and 1, is characterized by a larger correction at high pressure (lower altitude) and a shape much different from the others.

This approach is interesting since every pump has a specific correction profile. However, the b values determined in the laboratory and by adjustment to the ozone column do not agree well. The laboratory values being generally lower by a factor 2 to 3.

3.2.4 Comparison of BM pump correction on the SONDEX96 dataset

The various options described above for the pump correction profiles are applied to the SONDEX96 dataset. The differences are then calculated using the standard pump efficiency correction as the reference. In fig. 6, the profiles of these differences are reported as a function of the altitude.

The lines ***+P-H1+D***, resp. ***+P-H2+D***, correspond to the difference profile generated by substituting the standard pump correction by H1, resp. H2, in the processing of the BM data. The result is a decrease of the tropospheric and lower stratospheric ozone between 4 and 6% compensated by an 8 to 10% increase of ozone above 30 km. The Uccle correction is similar to H1 in the troposphere and to the standard correction in the stratosphere.

The difference between the ***+P-Std*** and the reference ***+P-Std+D*** curves reflects the averaged scaling factor of ~6.5% for the BM soundings of SONDEX96. The corresponding scaling factors for H1 and H2 corrections are ~2.5% and ~1% respectively. The decrease of the scaling factor is due to a larger E(z) term in equ. 1 which increase the amount of ozone deduced from the sonde .

The Uccle correction doesn't have a scaling factor since the scaling is done in the determination of the b parameter (see §3.2.3).

In conclusion, adopting H1 or H2 corrections induces a decrease of tropospheric ozone and an increase of stratospheric ozone. The scaling factors are also significantly reduced. Uccle procedure is quite similar to the standard treatment with a marked change restricted to the lower troposphere.

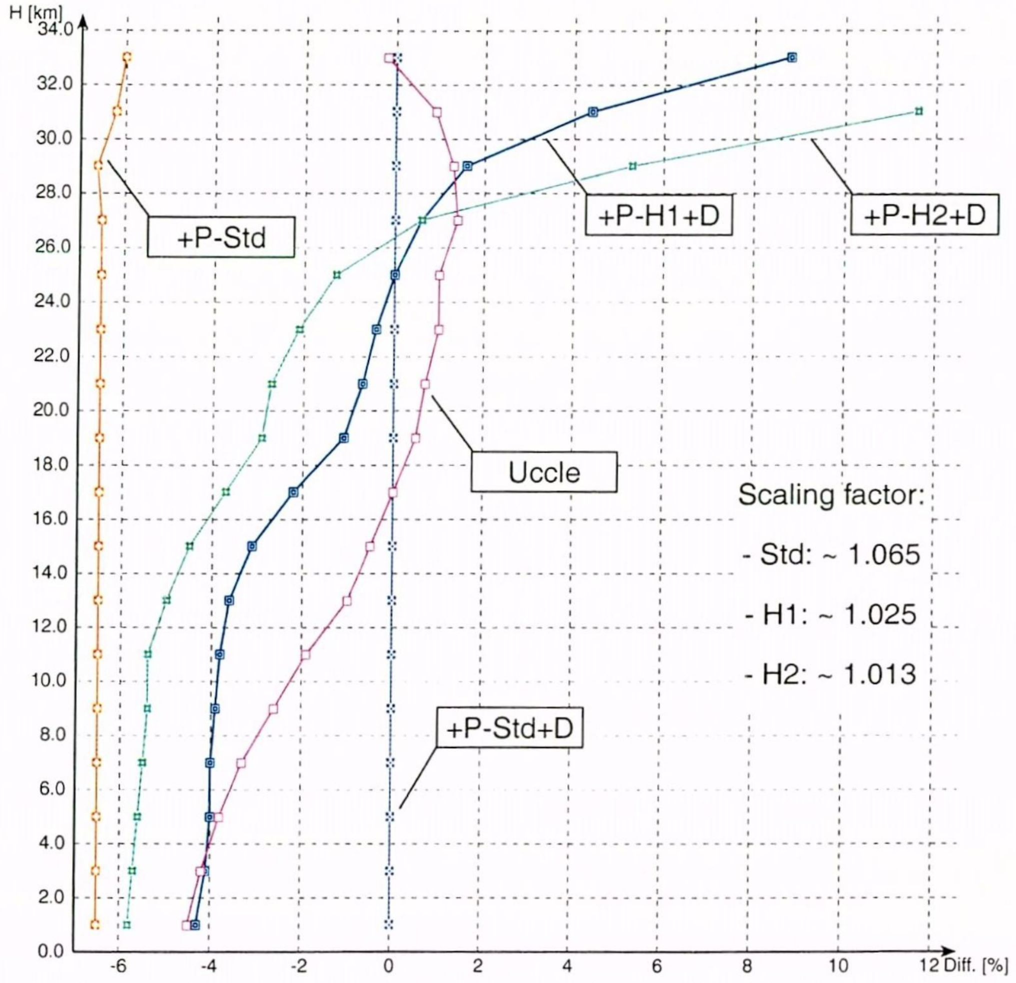


Fig. 6: Relative difference profiles for the BM data calculated with three different pump efficiency corrections (see text). The reference line corresponds to the standard processing. In the insert, the corresponding scaling factors are given. For the notation, refer to "List of symbols" at p. 17.

3.2.5 ECC correction profiles by Komhyr

For ECC sondes, two pump efficiency correction profiles have been published by Komhyr, 1986 and by Komhyr et al, 1994. Two different methods have been used, a bag inflation technique in 1986 and the "Table Mountain" technique in 1994. These two correction profiles are illustrated in fig. 7. They are quite similar down to 10 hPa, but differ below.

In contrast to BM sondes, there is no standard correction profiles due to the absence of an SOP. Presently, the manufacturer recommend the Komhyr, 1986 correction for the SPC sondes and the Komhyr et al, 1994 correction for the ENSCI sondes.

3.2.6 ECC correction from GFSC

The GSFC team uses for its ECC sondes a specially equipped pressure chamber to determine the pump corrections for every sondes (Torres, 1985). It is based on a constant volume technique and the measurements are performed between 60 and 6 hPa. Between 1000 hPa (efficiency=1) and 60 hPa, a linear interpolation is used. A three-coefficient function of the form:

$$E(p) = A_0 + \frac{A_1}{p} + \frac{A_2}{p^2} \qquad (3)$$

is adjusted to the calibration points. The correction profiles for the set of ECC sondes used in SONDEX96 campaign are given in fig. 7. The spread is relatively small between the curves. The two profiles by Komhyr give a higher correction than the GFSC ones between 100 and 20 hPa. At 10 hPa, the values measured at GSFC are between 1.03 and 1.07 in agreement with Komhyr's 1994 results. Between the various ECC pumps corrections, the differences are of the order of ~2% which are much less important than the differences seen between the various BM pump efficiency corrections (comp. fig. 5).

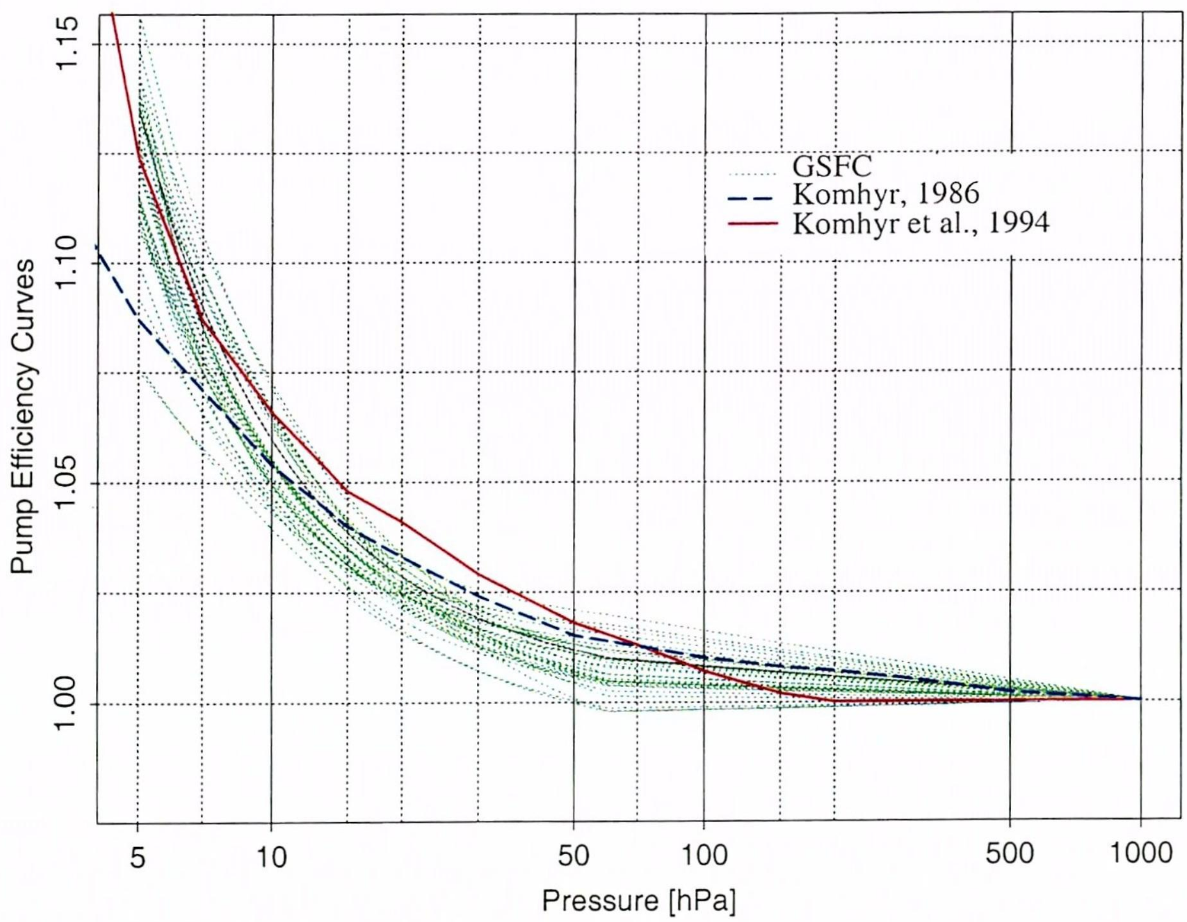


Fig. 7: ECC pump efficiency correction profiles. The mesh of lines corresponds to the corrections of the SONDEX96 ECC sondes measured at GSFC.

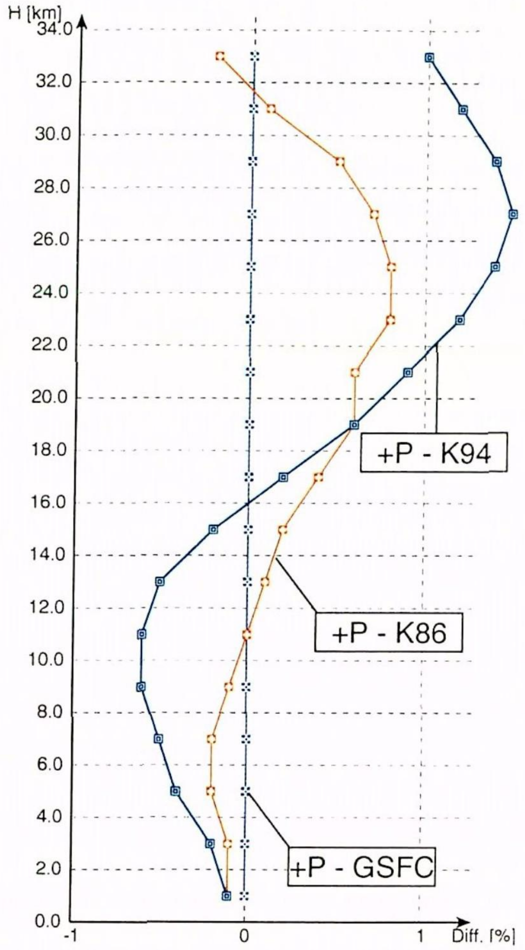


Fig. 8: Relative difference profiles for the ECC data calculated with three different pump efficiency corrections. The reference corresponds to the GSFC processing. K94 correspond to Komhyr et al., 1994 correction profile and K86 to Komhyr, 1986 correction profile. For the notation, refer to "List of symbols" at p. 17.

3.2.7 Comparison of ECC pump correction on the SONDEX96 dataset

Similarly to the BM case, the different ECC pumps corrections have been applied to the SONDEX96 data and the resulting relative difference profiles are given in fig. 8. The reference on this figure is the GSFC procedure. The differences stay confined between -0.8% to +1.5% which is much less important compared to the differences for the BM sondes (see fig. 6). This probably reflects the better reproducibility of the teflon ECC pump while the BM pump performances are less stable and depend for example, on the amount of lubricant.

3.2.8 Summary for pump efficiency correction

In summary, the pump efficiency correction is still an open question because the experimental determination of the corrections depends on the method used in the different laboratories. The differences and variability are particularly large at low pressure ($p < 10 hPa$). It can be estimates that for the BM sensors, the order of magnitude of the uncertainty for the correction is ~10% while for the ECC sensors it is ~ 2%. As seen in fig. 6, the redistribution of the ozone over the entire profile due to the Dobson scaling depends therefore on the selected pump efficiency correction profile.

3.3 Pump temperature correction $T_p(z)$

It is necessary to know the air temperature at the entrance of the pump to convert the volume flow rate to a mass flow rate of the ozone entering into the bubbler. A representative temperature is presently measured close to the pump, T_p, while in the past, the temperature sensor was measuring the inner styrofoam box temperature.

3.3.1 BM pump temperature

For historical reasons, no temperature measurements were operationally performed on BM sondes and a *constant* value for T_p is used in equ. 1. This constant temperature is function of the thermal insulation of the Styrofoam box and of the power dissipation of the battery and electronic board which is specific to each system. In 1995, the pump temperature has been measured during different soundings and a mean value of 280K was determined for the Payerne BM sonde set-up (Giroud, 1996). This value is smaller than the 300 K recommended in the BM SOP (WMO, 1987). The exact value for T_p is less important since it only changes the scaling factor. For example, setting T_p at 280k instead of 300K at Payerne increases the scaling factor by ~7% but doesn't change the final ozone profile. More recently, pump temperature have been recorded at Payerne and a mean profile $T_p(z)$ has been calculated. It is used to estimate the effect of substituting the constant T_p (=280K) value by $T_p(z)$ to retrieve the measured ozone from equ.1.

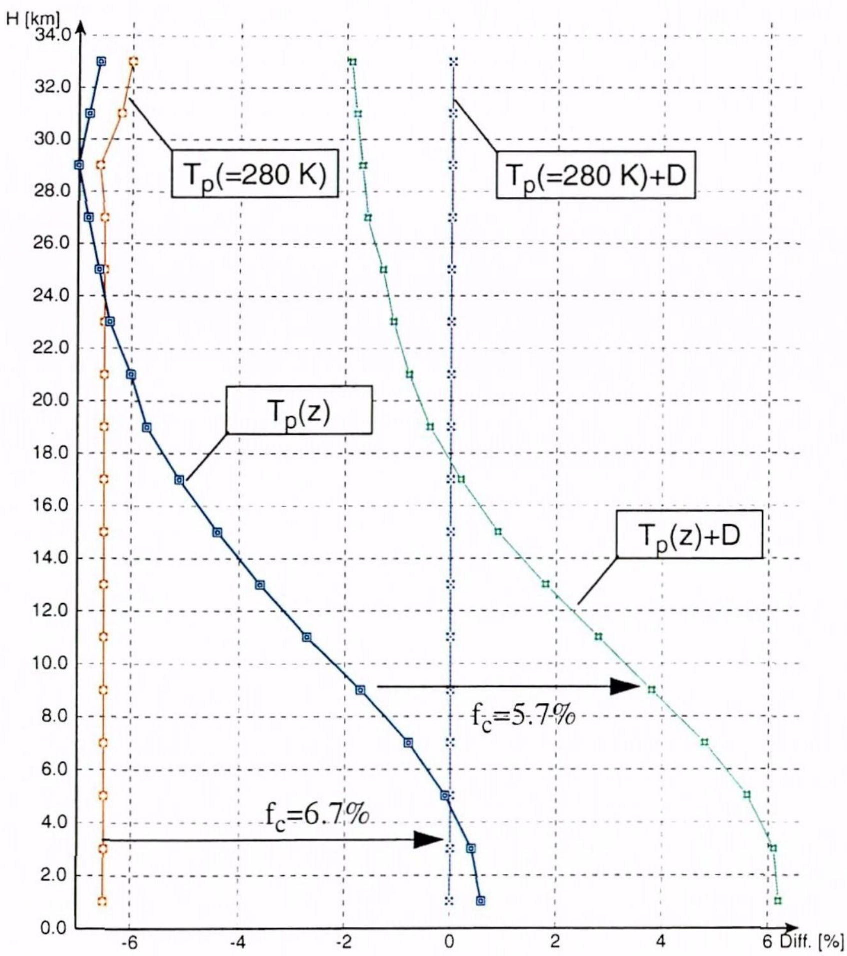


Fig. 9: Relative difference profiles induced by substituting a constant pump temperature (T_p = 280K) with a realistic profile $T_p(z)$. The reference corresponds to the constant T_p case. For the notation, refer to "List of symbols" at p. 17.

In fig. 9, the relative difference profile, $T_p(z)+D$, is reported for the SONDEX96 dataset with the standard treatment ($T_p(=280K)+D$) used as the reference. The difference is positive, ~+6%, from the ground to the low stratosphere (0-18 km) and negative, ~-2%, at mid-stratosphere (33 km).

The two curves on the left side ($T_p=280K$ and $T_p(z)$) correspond to the data before the Dobson scaling. They cross at the altitude of 24 km where the average pump temperature is at 280K. The scaling factors, illustrated by the arrows, are not substantially different, ~1%. Nevertheless, the low altitude ozone values are increased by ~5%. The constant pump temperature rule creates an artificial bottom-up transfer of ozone due to the Dobson scaling.

3.3.2 ECC pump temperature

For the ECC sondes, $T_p(z)$ is measured during each flight. The position of the temperature sensor is differs from laboratory to laboratory, being attached to the inlet tube, outlet tube or on the pump body. Various experiments have been performed in the ECC sondes and it has been found that the air is quite rapidly brought at thermal equilibrium close to the pump temperature. This implies that the exact position of the thermometer shouldn't make a large difference. The GSFC team taped the thermometer on the wall of the inlet teflon tube close to the pump.

During SONDEX96, the ECC pump temperature measurements were perturbed by electronic interferences in many flights and have needed corrections. Most of the bad temperature readings were found at altitudes lower than 16 km. An empirical correction has been applied which consists in replacing the bad part of the temperature profiles by a polynomial function of the altitude. The coefficient of the polynomial function have been adjusted on unperturbed fligths. The largest adjustment of the measured pump temperature is 15K in flight 15 and ten flights have been corrected by more than 5K. In fig. 10, the results of this treatment is emphasised by the line labelled ***T_p measured*** which corresponds to the relative difference profile between the measured and corrected pump temperatures. The largest difference at 5 km stay below 1%.

In fig. 10, the $T_p=280K$ curve has been produced by imposing a constant pump temperature to the ECC data similarly to the BM data of fig. 9. It appears that the range of the difference is ~ 5%, from -3% at the ground to 2.2% at 33km. This lower range corresponds to a better thermal insulation of the ECC package or a larger dissipation of energy (electronic circuits, battery, ...) in the box that prevents the drop of the pump temperature at high altitude.

3.3.3 Summary for pump temperature correction

The use of a real temperature profile instead of a constant value in the BM data processing affects mostly the tropospheric ozone values up to ~15 km (see fig. 9), but doesn't affect much the correction factor. The pump temperature is treated differently for the BM and ECC sondes which induces a systematic bias of the BM tropospheric ozone values of the order of -5%.

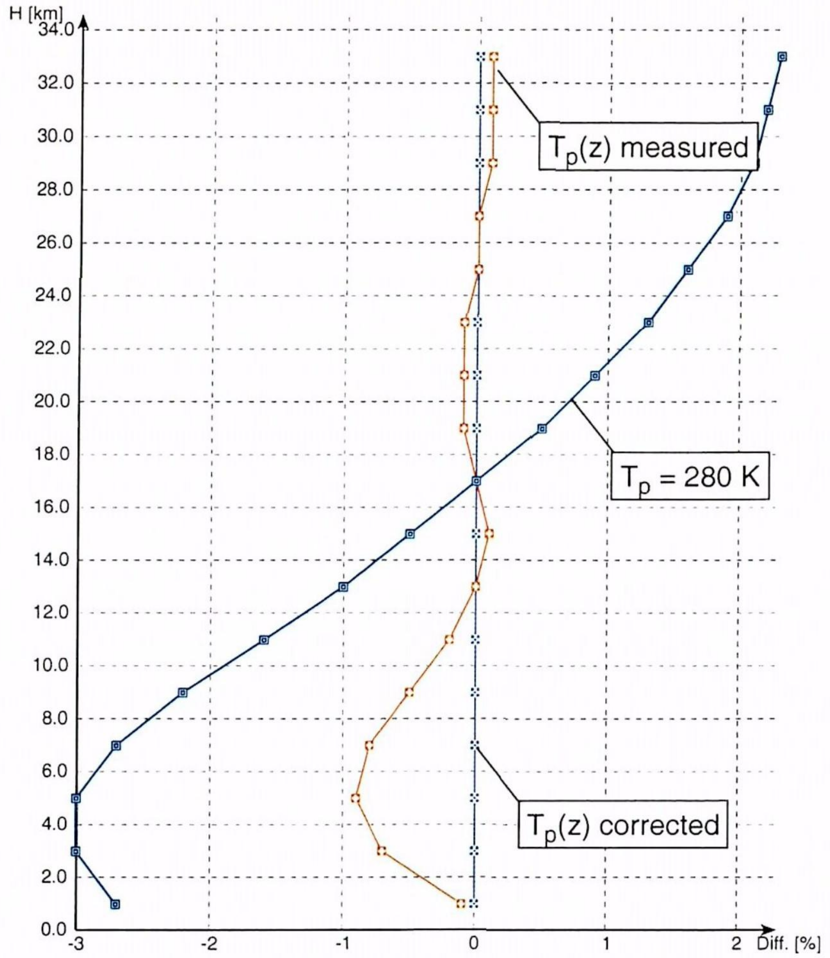


Fig. 10: Average difference profiles for ECC ozone calculation. The reference are the data with the corrected pump temperature. The measurement problems generate the largest difference in the middle troposphere. The ***T_p=280K*** *difference curve is found when a constant T_p is imposed to the ECC data. For the notation, refer to "List of symbols" at p. 17.*

3.4 Background current

It is observed in all sondes types that the cells hardly measure a zero amount of ozone at the ground. This residual ozone or background current is possibly due to residual impurities from cleaning in the BM cells. In the ECC, the ion bridge might be the cause of the back-ground current and also impurities residing in the anode and cathode cells.

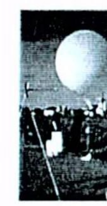
As mentioned in table 2, the ECC data processing incorporate the background subtraction while in the BM case, it is ignored.

3.4.1 ECC measured background current

Two background currents are measured in the ECC preparation procedure: i_{b1} is measured before exposure to ozone and i_{b2} is measured after exposure to ozone just before release of the ozonesonde into the atmosphere. It was recommended in former ECC sonde operating manuals, to reduce the residual ozone as lower pressures are reached during the ascent of the sonde. The experiences conducted in different laboratories, in particular at the Jülich simulator, do not corroborate such a decrease and a constant back-ground current is presently advised in the ECC community. For SONDEX96, i_{b2} is used in the data processing and it is assumed constant throughout the flight.

3.4.2 BM estimated background current

The background current is not measured in the BM sondes and therefore sets to zero in the data processing as specified in the SOP (WMO, 1987). During the preflight procedure for the BM sondes in Payerne, a four points calibration with a reference UV photometer is routinely performed and used as a quality control of the delivered sondes. This calibration allows the estimation of the background current in two ways: first the "position 0" (pos0) corresponds to the ozone value measured by the sonde when the ozone generator is switch off (resolution 1 nbar). Secondly, the "offset" is the result of a linear fit through the four calibration points. The offset values are in most cases smaller than the pos0 values. Both estimates of the residual ozone are used in the analysis. There is no measurement of the residual ozone performed before exposure ($\sim i_{b1}$) to high ozone concentration in the present BM preparation procedure.



To evaluate the effect of the residual ozone on the BM results, the SONDEX96 dataset was reprocessed subtracting the two estimates of the residual ozone mentioned above (pos0 and offset) and these two series are compared to the standard processing. In fig. 11, the relative difference profiles are reported with the standard processing as the reference. As expected, the larger differences are found in the troposphere were the ozone concentration is small. A decrease of ~-5% and ~-10% are found for respectively the

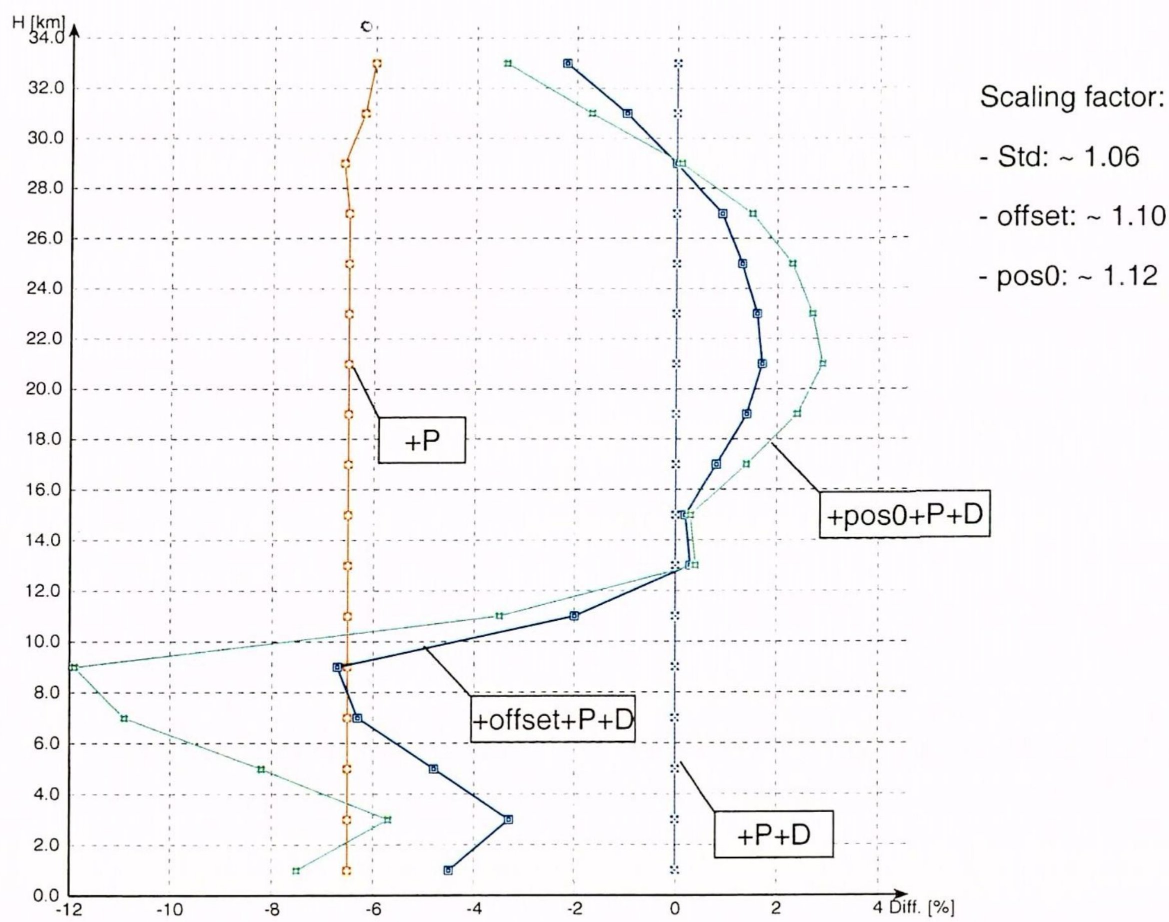


Fig. 11: Average difference profile for the BM dataset processed with two estimates of the residual ozone. The reference serie is the standard processing, which doesn't include residual ozone. For the notation, refer to "List of symbols" at p. 17.

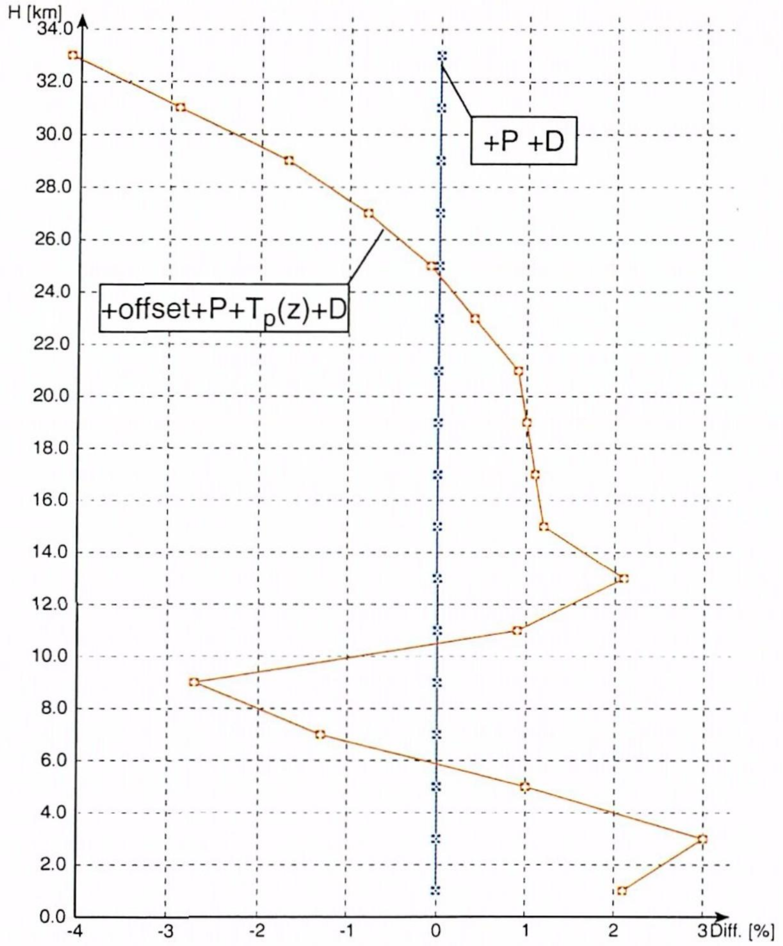


Fig. 12: Average profile difference for the BM data processed with the $T_p(z)$ and the residual ozone (offset) effect compared to the standard processing as reference. For the notation, refer to "List of symbols" at p. 17.

offset and pos0 residual ozone estimates. The decrease of tropospheric ozone is compensated, due to the Dobson scaling, by an increase of ~2% to ~3% at the altitude of the ozone layer between 20 and 25 km. The scaling factor is significantly increased from 1.06 (standard) to 1.10 (offset) and 1.12 (pos0) respectively.

In the previous paragraph, it was shown that taking into account the pump temperature for the BM sonde increases the tropospheric ozone while in the present paragraph, removing the residual ozone from the measurements reduces it. In fig. 12, the combined effect of these two contributions is presented for the "offset" case. The relative difference profile is characterised by an increase of the ozone below 25 km and a decrease above 25 km. But the differences are confined within ~±3%. It appears that pump temperature and residual ozone effects compensate each other which is an argument for keeping the simple data processing specified in the BM SOP.

In summary, the back-ground current producing the residual ozone has a major effect in the troposphere. The Dobson scaling produces an increase of the ozone at the altitude of the ozone layer to compensate the decrease in the troposphere. Applying simultaneously the corrections for the pump temperature and the background current produce a net effect of relatively low importance of the order of ~±3% as seen in fig. 12.

4. Results of BM - ECC comparisons

In this section, the differences between BM and ECC ozonesondes are presented. The effects discussed in section 3 are used to simulate different options for the processing of the BM dataset. The comparison with the ECC measurements allow to judge the importance of the different factors and their combinations.

In the results presented below, the average relative differences profile are given as a function of the altitude with the ECC sonde data selected as the reference. This choice is arbitrary and does not mean that the ECC sonde is an established reference system. However, in general the order of magnitude of the correction applied to the ECC raw data and the variability of the measurements are lower than for the BM sonde. As outlined in table 2, the ECC data are generally presented without scaling to the Dobson total ozone. For the presentation of the SONDEX96 results, this practice has been adopted and therefore the series ***ECC+P*** is the reference for the relative difference calculation.

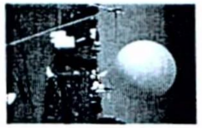
When a relative scale is used, two profiles which differ only by a scaling factor result in parallel lines. This is also true for the averages of an ensemble of profiles if all profiles reach the same altitude. In the SONDEX96 data set, this last condition is not fulfilled since the balloons blow up at different altitudes. Therefore in most of the figures, it will appear that the expected parallelism is distorted at high altitude.

The general picture that comes out of the SONDEX96 campaign is summarised in fig. 13a by the ***BM+P+D*** line corresponding to the difference profile between the BM and ECC sondes. BM ozonesondes indicate higher ozone up to 21 km, with a maximum of +8% at the tropopause level. Above 22 km, the difference is negative, reaching -11% at the top of the profile. The average ozone amount at 9 km is about 30 nbar consequently the observed +7% difference corresponds then to ~2 nbar. At 30 km, the average ozone partial pressure is ~ 70 nbar, thus the -11% difference corresponds to -8 nbar. These estimates show that the main concern is in the upper part of the profile while in the tropopause region the difference is close to the noise level of this type of measurements.

Those differences are obtained with the standard treatments summarised in table 2 (section 3) applied to the BM and ECC datasets. In the next sections, the consequences of different data processing for both ozonesonde types are quantified and it is shown to which extend the discrepancy observed in fig. 13a can be explained.

The other curves in fig. 13a illustrate the different steps of the data processing and give the following information:

- the ***ECC+P+D*** line shows the effect of the Dobson scaling which on average decreases the data by 1.5%. This gives a mean scaling factor of 0.985 for ECC.
- the ***ECC*** line, corresponding to the raw data, illustrates the averaged pump efficiency correction of the 29 individual ECC sondes obtained with the GSFC procedure.
- similarly, the ***BM*** line shows the difference of the BM raw data which are systematically lower than the ECC data except at the tropopause.



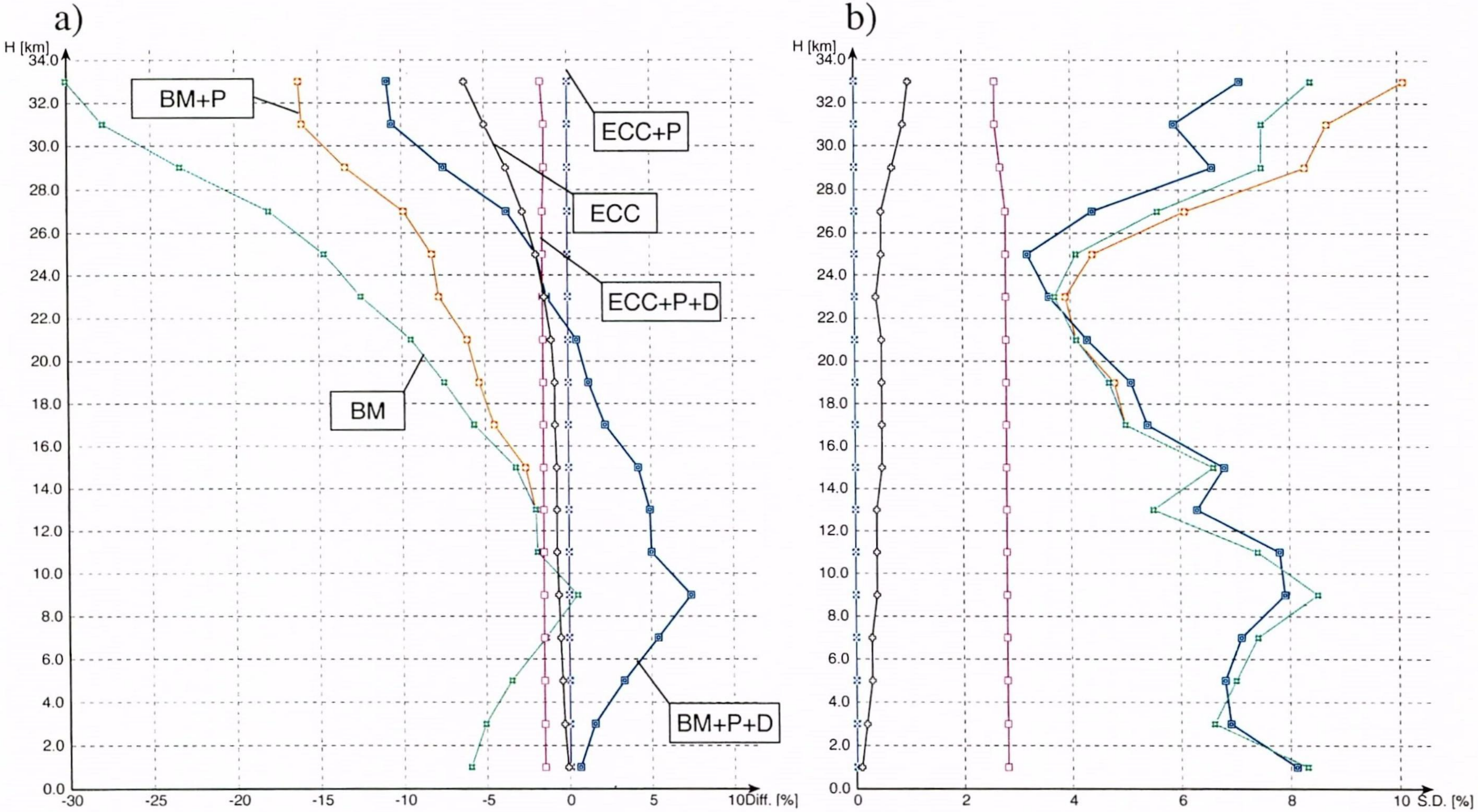
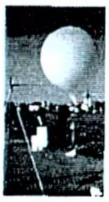


Fig. 13: (a) Relative differences (BM-ECC)/ECC. The curves illustrate the different steps of the data processing (see text). For the notation, refer to "List of symbols" at p. 17. (b) Same as (a) for the standard deviations.

- the ***BM+P*** line is the difference after correction for the loss of pump efficiency. The correction is of the order of 15% at 33 km.
- the ***BM+P+D*** lines corresponds approximately to the ***BM+P*** line shifted to the right by the mean scaling factor (~7%) of the SONDEX96 BM data. Due to the large deficit of ozone of the BM in the upper part of the profile, the differences in the troposphere change sign when the Dobson scaling is applied.

Figure 13b gives the standard deviation in [%] associated with the different curves of fig. 13a. It demonstrates the larger variability of the BM data, notably in the troposphere and in the upper part of the sounding (above 25 km) where the ozone amounts are small.

Fortunately, the parameters reported in table 2 and discussed in paragraph 3 affect the ozone at different parts of the profile with a main emphasis on i_b in the troposphere, on $T_p(z)$ in the lower stratosphere and E(z) in the upper stratosphere. The Dobson scaling affects the entire profile. This allows to discuss separately the different contributions before grouping them at the end.



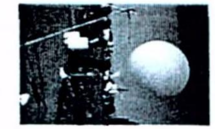
4.1 Background currents and pump temperature effects

The BM data processing presented in this paragraph duplicates the ECC processing and allows to compare data treated in a similar approach concerning the background current and the pump temperature profile. In fig. 14, the relative difference between the ECC data (ref.: ***ECC+P***) and four versions of the BM processing are illustrated with the full profile in fig. 14a and an enlargement on the troposphere in fig. 14b. These treatments are:

- ***SOP***: the standard processing +P+D,
- ***SOP+offset***: residual ozone is subtracted,
- ***SOP+Tp(z)***: $T_p(z)$ is used instead of the constant 280 K,
- ***SOP+offset+Tp(z)***: both corrections are applied simultaneously.

The residual ozone subtraction on BM data (***SOP+offset***) has a impact below 13 km in decreasing the difference with the ECC. The real pump temperature profile (***SOP+Tp(z)***) increases the difference in comparison with the ECC data up to +12% at 9 km. Both corrections superimposed (***SOP+offset+Tp(z)***) present a difference of about +5% difference over most part of the troposphere and little effects in the stratosphere. This processing of the BM data is similar to ECC except the Dobson scaling which would shift the ECC reference line by 1.5% to the left.

The compensating effects of the two factors is in favor of the SOP which doesn't take them into account in the BM data processing. This argument holds as long as the design of the sonde and the preparation procedure are not changed over time. The pump temperature profile is determined by the thermal insulation of the sonde and the power dissipation in the box. Changing these parameters would affect $T_p(z)$. As for the residual ozone, the preparation procedure is crucial. It is expected that the compensating effect could have changed with time and could be responsible for discontinuities in the series, mainly affecting the tropospheric ozone. On the other hand, no direct measurements are available to proprely handle these parameters back to the beginning of the sounding series.



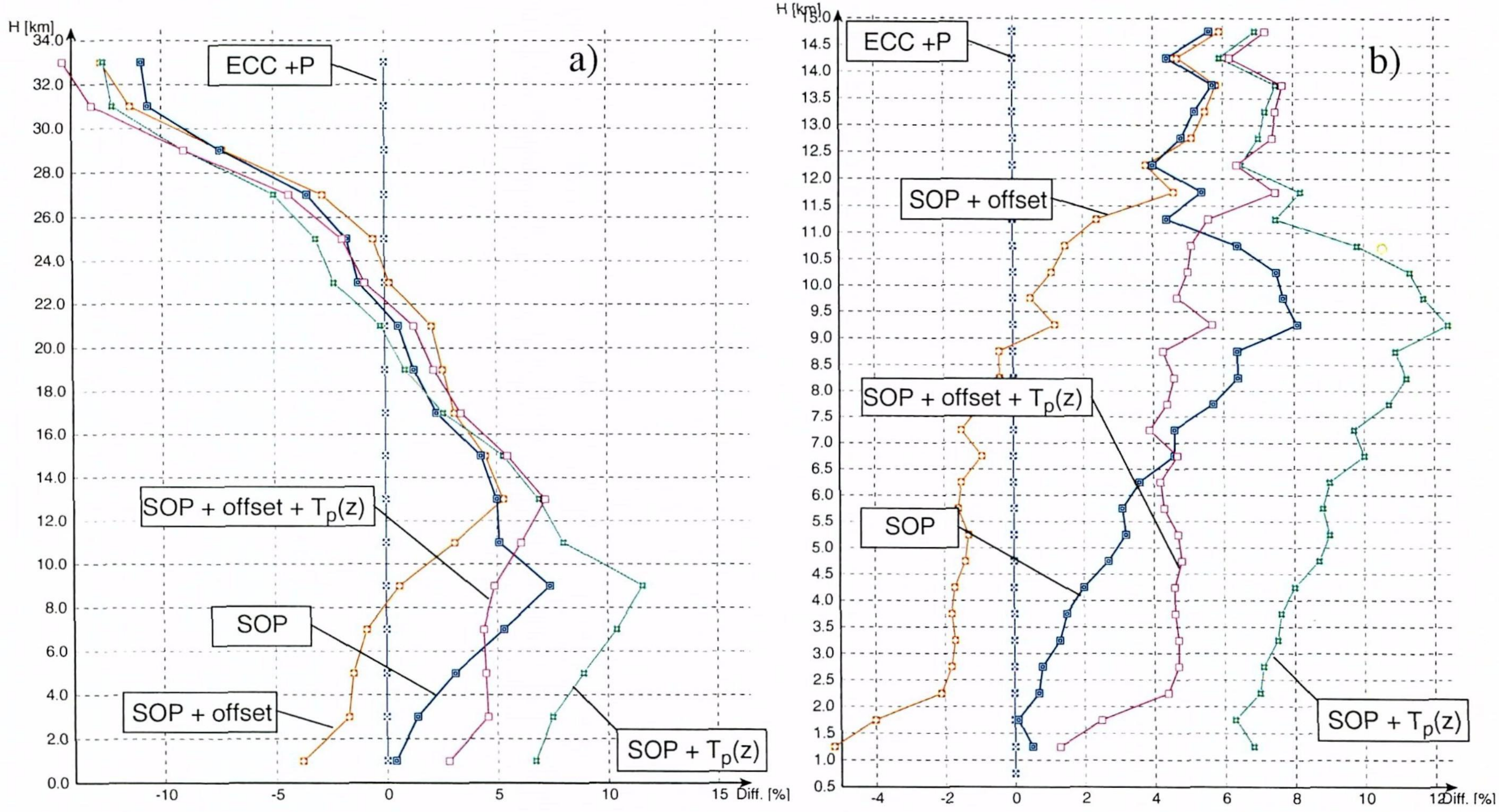
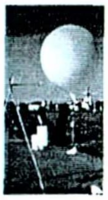


Fig. 14: Difference profile (BM-ECC)/ECC with emphasis on the residual ozone and pump temperature profile in the BM data processing. The (a)-panel show the entire profile up to 34 km while the (b)- panel is a zoom on the troposphere up to 15 km. For the notation, refer to "List of symbols" at p. 17.

4.2 Pump efficiency effect for BM

The major discrepancy between the ECC and BM is found in the upper stratosphere which is currently thought to be a loss of the BM pump efficiency not fully compensated. As described in §3.2, different alternatives for the BM pump correction profiles have been proposed in the literature. The BM data have been calculated with four different pump efficiency corrections. In fig. 15, the relative difference profiles between the ECC data and the four BM series are given. The scaling factors calculated for these data are respectively 1.07 for the standard pump correction, 1.025 for the H1 and 1.01 for H2. The Uccle treatment has a factor of 1 by definition of the procedure.

With these larger corrections (H1 & H2) for the loss of efficiency of BM pump compared to the standard curve, it appears that the profile of the differences between BM and ECC is markedly changed: the positive difference from the ground up to 20 km for the standard treatment is largely reduced and change sign when a larger pump efficiency correction is applied.



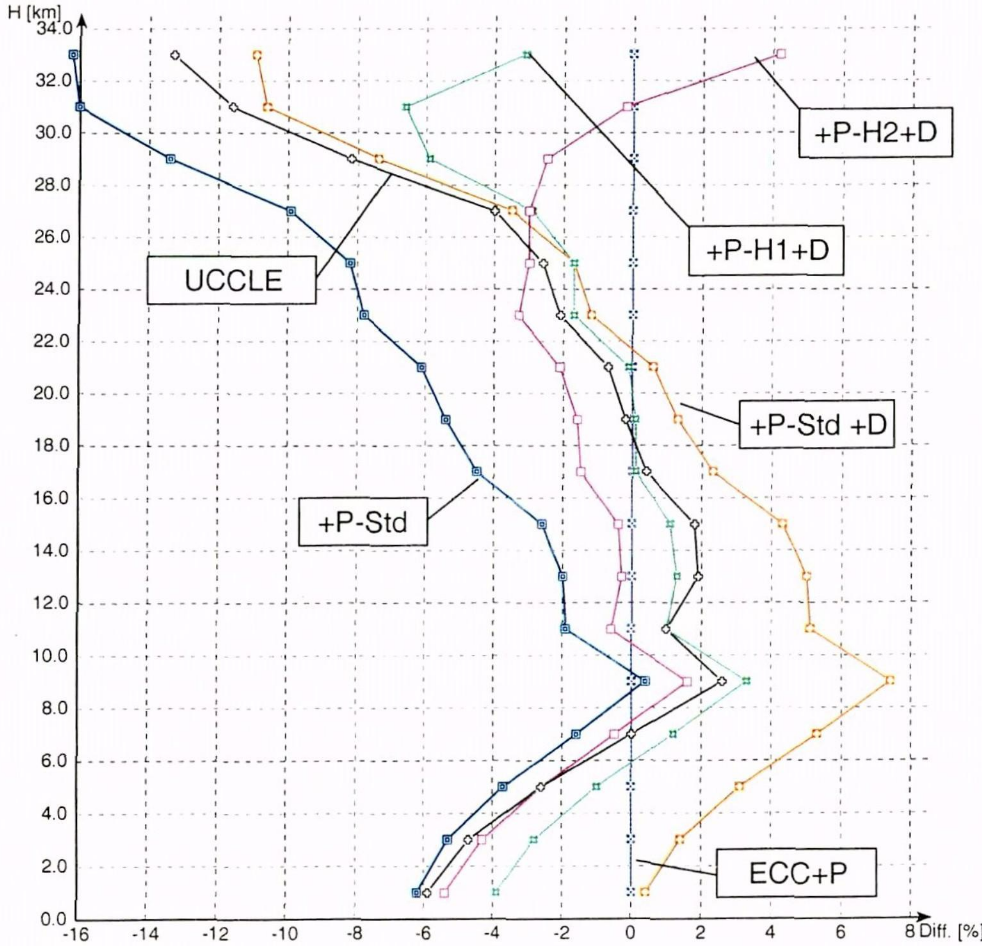


Fig. 15: Difference profiles (BM-ECC)/ECC calculated with different pump efficiency correction for the BM dataset: Standard, H1 and H2 curves from Hohenpeissenberg and the Uccle procedure. For the notation, refer to the list of symbols at p. 17.

The H2 correction tends to overcorrect the data resulting in an overestimate of ozone from BM sonde compared to ECC for altitude higher than 30 km. The intermediate H1 correction is the most appropriate in this case with an s-shape difference profile lower than ± 5%.

The Uccle procedure affects the upper troposphere-lower stratosphere region giving satisfactory results up to 27 km. Higher up, this processing doesn't correct sufficiently the BM pump efficiency loss. That means that the parametric relation (equ. 2) used to model the pump behaviour isn't sufficient at low pressure. In the lower stratosphere (below ~27 km), the Uccle correction increases the ozone values in a way similar to the H1 and H2 correction. In the troposphere, it doesn't change much the ozone amount considering that the normalisation to the Dobson value is included in this procedure.

It is interesting to note that the three alternative processings give comparable results to ± 1% over the altitude range 1-27 km and that they agree quite well (± 4%) with the ECC data.

In summary, it appears from fig. 15 that the different alternatives to correct the loss of pump efficiency has a large influence on the comparability of BM and ECC sondes. Up to 27 km, the agreement is good if the pump efficiency correction is larger (e.g H1-curve) than the standard correction recommended in the SOP.

4.3 Superposed corrections for BM sondes

The synthesis is obtained by incorporating simultaneously in the BM processing $T_p(z)$, the residual ozone and either the standard, H1 or H2 pump efficiency correction. The relative difference profiles between the ECC data and these three BM series is presented in fig. 16. The H2 correction produces the best agreement with a difference within ± 4% of the ECC data over the entire profile. The largest differences are at 13 and 29 km. The H1 correction still preserve a quite good agreement up to the altitude of 27 km. The standard correction produces a 5-7% difference up to 15 km and a regular decrease to -14% at 33 km. Since the order of magnitude of the observed differences between ECC and BM-H2 processing are within a few percents, the scaling of the ECC data is recommended to achieve a complete processing similarity.

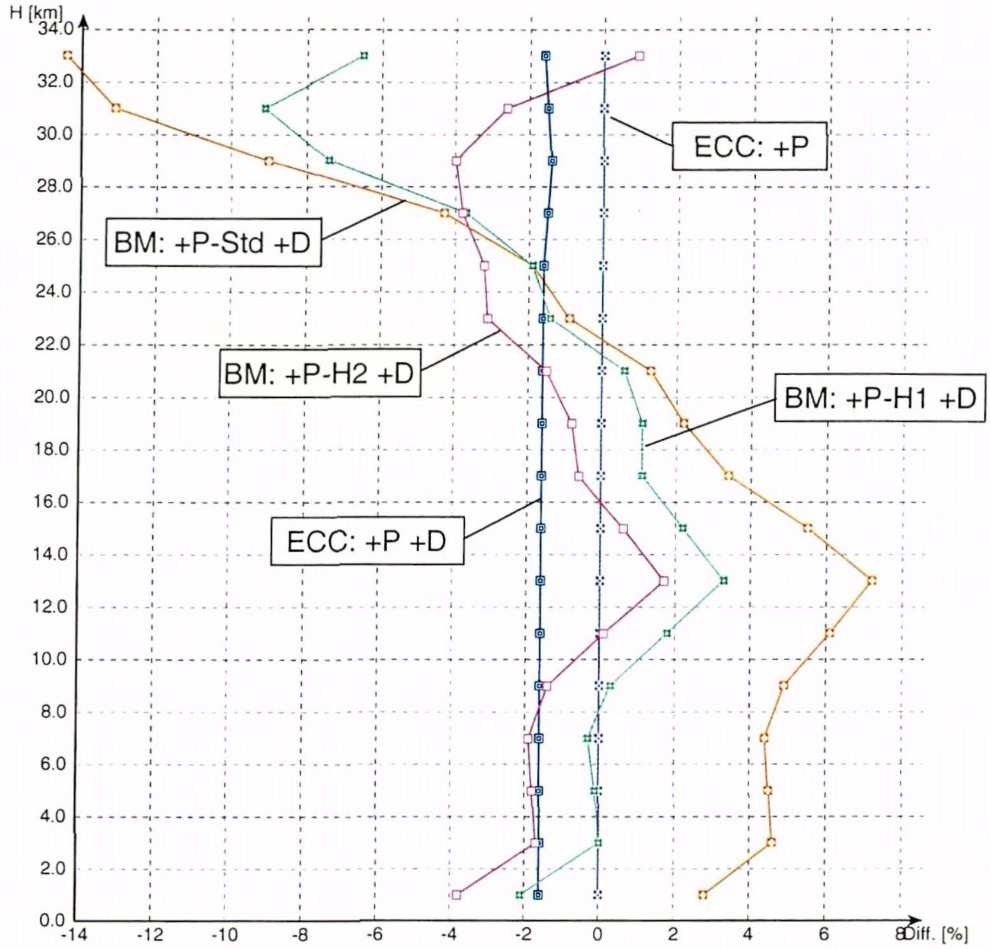


Fig. 16: Average difference profile (BM-ECC)/ECC for the combination of pump temperature and residual ozone effect associated to the two alternate pump efficiency corrections from Hohenpeissenberg. For the notation, refer to "List of symbols" at p. 17.

4.4 SPC vs ENSCI ECC sondes

As mentioned in §2.3, ECC sondes from two different manufacturers have been used during SONDEX96 campaign. All ECC sondes have been prepared along GSFC procedure even if the manufacturers recommendations are slightly different. The post-processing of the data is similar too.

In fig. 17, the relative difference profiles are reported for the complete SONDEX96 dataset and the two subsets consisting of 20 SPC/ECC and 9 ENSCI/ECC ozonesondes. The observed differences between the two subsets are significant, the SPC being closer to the BM than the ENSCI. The main differencc is the spreads of the difference profiles, the ***"BM vs ENSCI"*** line stretches over 27% (-16% to +11%) while the ***"BM vs SPC"*** line covers 16% (-10% to +6%). From this observation, it is not possible to say which of the ECC is closer to the reality but similar behaviour has been observed in Jülich simulator (Smit et al., 2000). The BM scaling factors differ by 1.5% (see fig. 17) between the two subsets while the SPC and ENCI scaling factors are the same at about -1.6%.

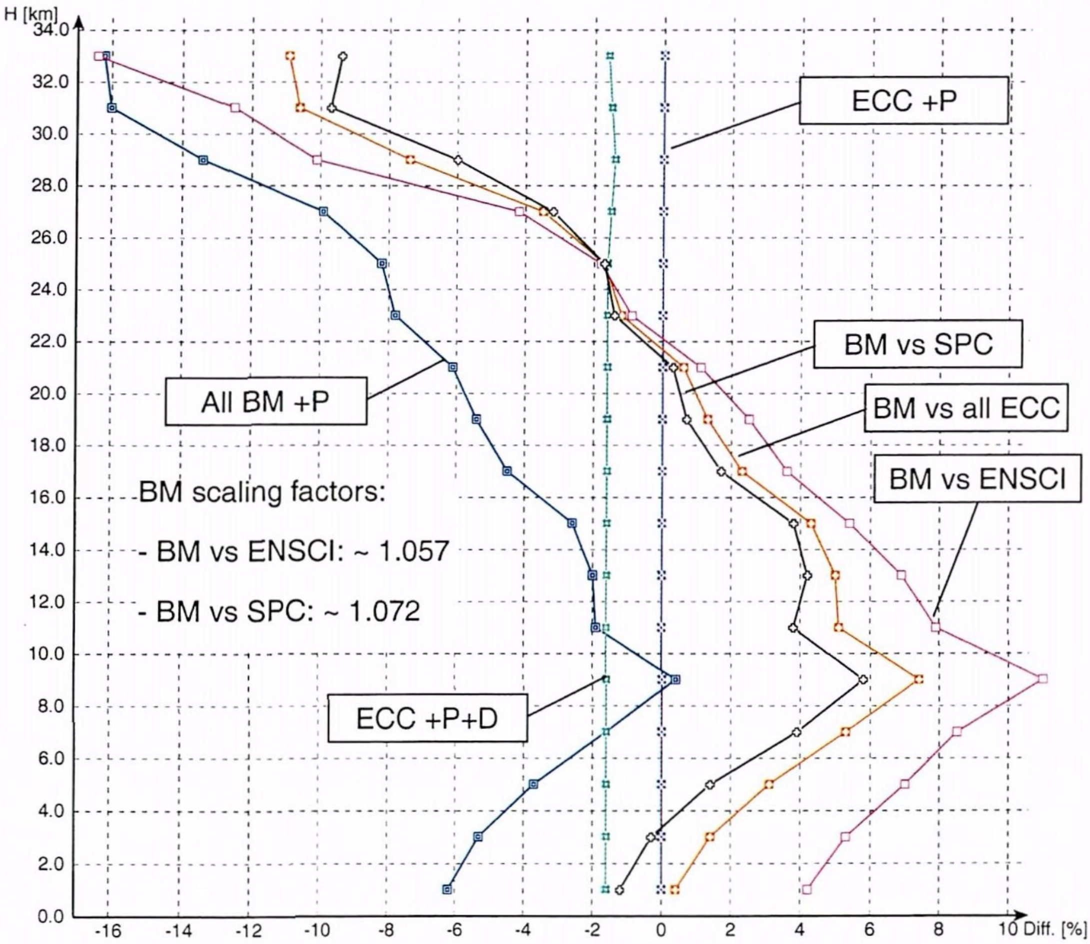


Fig. 17: Relative average difference profile (BM-ECC)/ECC for the SONDEX96 dataset splitted according to ECC sonde type. The reference are always the ECC ozonesonde data. For the notation, refer to "List of symbols" at p. 17.

5. Conclusion

The SONDEX96 experiment was a part of the ongoing activities to improve the ozone sounding measurement technique in the framework of the Swiss Global Atmospheric Watch (GAW/WMO) programme. This campaign had two majors aims, first to ascertain the comparability of the BM and ECC sondes in atmospheric conditions and second to evaluate the sensitivity of this result to the data processing. A third point was the feasibility study of combining the two sondes in a hybrid system (BM cells with ECC pump). Unfortunately, this hybrid system didn't work properly for technical reasons and didn't produce valuable data.

In this report, the ECC measurements were selected as the reference in most of the comparisons. This choice is arbitrary and does not mean that the ECC sonde is an established reference system. However, in general the order of magnitude of the correction applied to the ECC raw data and the variability of the measurements are lower than for the BM sonde.

This SONDEX96 campaign has produced the following main results:

- The standard data processing of the BM and ECC sondes are quite different and this has a large effect on the comparability of the two sondes,
- In the troposphere, the residual ozone and the initial drop of the pump temperature have large effects, fortunately, they compensate each other to a large extent,
- In the stratosphere, the pump efficiency correction is the dominant factor for the BM sondes. The different alternatives proposed in the literature do not agree with each other and have a large effect on the comparability of BM and ECC,
- In the SONDEX96 campaign, the correction factors of the ECC are close to unity. This means that the question of the scaling to the Dobson column is less important for ECC then for the BM sonde for which it is an essential element of the processing.

The limits of the differences profile between BM and ECC are ~±10% (see fig. 13) if the BM data are processed as specified in the SOP. As shown in §4., it is possible to reduce those limits to ±4%. However, to achieve this result it is necessary to processed the BM data similarly to the ECC data and to depart from the BM SOP.

Introducing the real pump temperature profile and taking off the background signal are certainly justified steps of the data processing. But the necessity to increase the pump efficiency correction is not supported by the laboratory measurements. In a recent publication from Uccle (De Baker et al., 1998), an extra temperature dependence is added on the pump efficiency correction. Its magnitude is on the order of 10% at 50hPa and 15% at 10 hPa. Such an extra temperature correction could explain the increase just mentioned. The determination of the pump efficiency correction remain a difficult task and the different laboratory results don't show a good consistency for BM and for ECC sonde.

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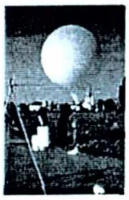

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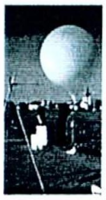

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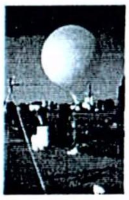


MeteoSwiss

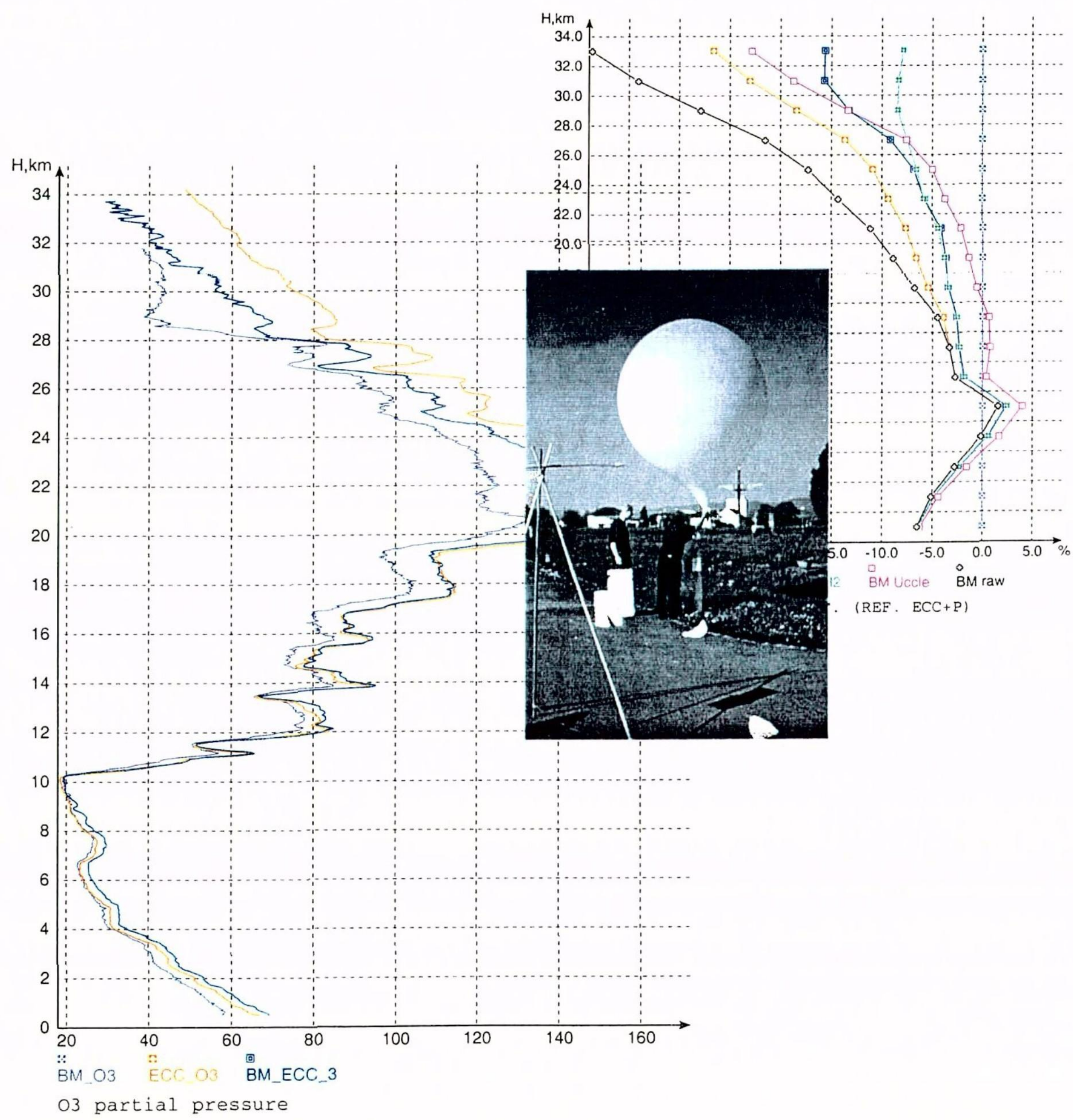
OZEX project:

ONE YEAR OF DUAL BM - ECC SOUNDING

Report on Data Processing

R. Stübi, Ch. Ammann

(Aerological Station of Payerne, 2001)



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List of symbols and abbreviations

BM	**B**rewer-**M**ast ozonesonde
BMpECC	BM ozonesonde with an ECC teflon pump
$E(z,T_p(z))$	Pump efficiency correction including the pump temperature dependance
ECC	**E**lectrochemical **C**oncentration **C**ell ozonesonde
ENSCI	ENSCI Corporation, provider of ECC ozonesondes
f_c	Scaling factor
GAW	**G**lobal **A**tmospheric **W**atch, WMO program
GSFC	NASA **G**oddard **S**pace and **F**light **C**entre
H1, H2	BM pump efficiency correction from Steinbrecht et al., 1997
i_{b2}	Back-ground current of an ECC ozonesonde
JOSIE	**J**ülich **O**zone **S**ondes **I**ntercomparison **E**xperiment
K86	ECC pump efficiency correction from Komhyr et al.,1986
K94	ECC pump efficiency correction from Komhyr et al.,1994
MeteoSwiss	Swiss Federal Office for Meteorology and Climatology
MOHp	**M**eteorological **O**bservatory **H**ohen**p**eissenberg, DWD
NASA	**N**ational **A**eronautical and **S**pace **A**gency
offset	BM residual ozone extrapolated from laboratory calibration
OP	**O**perating **P**rocedure
pos0	BM residual ozone measured in laboratory calibration
SONDEX96	Campaign of parallel BM - ECC soundings at Payerne
SOP	**S**tandard **O**perating **P**rocedure
SPC	**S**cience **P**ump **C**ompany, provider of ECC ozonesondes
$T_p(z)$	Pump temperature profile
WMO	**W**orld **M**eteorological **O**rganisation

List of labels in figures

...+D	Scaling of ozone profile with Dobson column is applied
...+P-H1	H1 pump efficiency correction is used
...+P-H2	H2 pump efficiency correction is used
...+P or +P-Std	Standard pump efficiency correction is used
...+P-K86	Pump efficiency correction from Komhyr, 1986 is used
...+P-K94	Pump efficiency correction from Komhyr et al., 1994 is used
...+T_p(=280K)	Pump temperature assumed to be constant at 280 K
...+$T_p(z)$	Actual or mean pump temperature profil
...+offset	Residual ozone correction applied using offset
...+pos0	Residual ozone correction applied using pos0

UCCLE	Pump efficiency and Dobson scaling according to Uccle procedure
SOP	Data processed according to **S**tandard **O**perating **P**rocedure for BM
$E(z,T_p(z))$	Pump efficiency correction dependant on altitude and pump temperature

List of figures

1. Introduction

At the MeteoSwiss Aerological Station in Payerne, atmospheric ozone profiles are recorded since 1968 and constitute one of the longest continuous series in the world. These observations are of major interest for the evaluation of the long term evolution of the stratospheric ozone layer as well as the tropospheric ozone (WMO,1999).

In Payerne the operational soundings have been made so far with Brewer-Mast (BM) ozonesondes. However, most of the stations and campaign teams around the world presently perform the measurements with the electrochemical concentration cell (ECC) ozonesondes which present a better technical reliability than the BM and imply much less efforts for prelaunch preparation. Furthermore, the supply of good quality BM sondes is becoming precarious and cannot be guaranteed on the long term. It is therefore planned to switch from BM to ECC ozonesondes as the operational system of Payerne station in the course of the year 2002. Any modification of the operational protocol, in particular a change of sonde type, would necessarily introduce a break in the time series. To minimize this disruption, a good preparation of the transition is necessary and the consequences have to be anticipated.

OZEX is a project set up by MeteoSwiss to investigate differences between ozonesondes of the type ECC and BM. More than ninety dual flights were released over the period March 1998 to June 2001 as part of the operational service. This long term comparison followed the previous short term SONDEX96 (Stübi, 2001) campaign and was designed with the following goals:

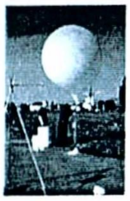
- Validate the conclusions reached with the SONDEX96 campaign,
- Perform the intercomparisons within the regular service to complement the short term campaign SONDEX96,
- Evaluate the consequences of a change of sonde on the consistency of the long term series.

At the methodology level, the ideal one would be deductive. From the knowledge of the chemical and physical principles of the two ozonesonde types, one should be able to deduce the difference between their measurements. This approach unfortunately fails here, due to the lack of experimental means and the impossibility to know *a priori* the state of the sample measured. As we can not easily test assumptions, the **inductive** approach will be used.

At the phenomenological level, due to the high variations of the meteorological parameters and the non-reproducibility of the measurement conditions, the sonde behaviour is better understood through **statistical** evaluation rather than through individual dual flight analysis.

1.1 Structure of the report

In section 2, a brief description of the two ozonesonde types and of the OZEX project design are presented. The processing of the ozone sonde data is described extensively in the SONDEX96 report (Stübi, 2001). In the present section 3, only a reminder of the basic equation is given and a complementary treatment concerning the temperature dependence of the pump efficiency correction is reported. In section 4, the analysis of the differences observed between the two types of ozonesonde is presented and analysed in a form similar to the SONDEX96 report to allow an easy comparison of the results. In section 5, the analysis of dual flights with sondes of the same type are presented. In section 6, the scenario of an hypothetical change of the sondes from BM to ECC at the beginning of the campaign is conceived. The consequence of that scenario are discussed in regard to the effect on the calculated trend at different levels. Finally, the conclusion summarizes the results of the project.



2. Project design

2.1 Field procedure

From March 1998 to May 1999, dual soundings have been performed once a week. Since June 1999, the frequency has changed to one dual flight each month until summer 2001. The two launched sondes are generally an ECC and a BM sondes but they are occasionally of the same type.

When the sondes are of different type, a careful comparison of the measurements in identical conditions allows to extract and ideally explain the differences between the two measurement devices. The differences in the variability and in the absolute measurements of the two sondes are quantified. When the two sondes are of the same type, the reproducible character of the measurement system can be evaluated.

The two sondes are attached under the balloon to a 2 meter long boom. The parameters are recorded as a function of time with two separate data acquisition systems. These are adjusted to within one second at the launch time. To individually compare pair of sondes, the time scale is the only accurate reference. Nevertheless time cannot be used any more when analysing several flights because of various ascending speeds. Altitude is used for those statistical comparisons. Altitude differences of about $\pm$ 50 m at 30 km are typically recorded in the dual flights producing negligible bias in the comparisons.

2.2 Technical considerations

The present BM and ECC ozonesondes are described in details in the technical report by Levrat and Hoegger (1999). The original work concerning the BM sonde has been published in 1960 (see ref. in Griggs, 1961). For an in-depth understanding of the BM instrument, the PhD thesis of M. Griggs (1961) is recommended. The ECC sonde has been designed by W. Komhyr and the related publications can be found in Komhyr, 1969, Komhyr,1986 and Komhyr et al., 1994.

To summarize the content of the Levrat's report, we recall that the two sondes do not function on the same chemical principle as the BM is a battery where both the silver anode and the platinum cathode are plunged in the same solution bath while the ECC is a common galvanic battery where the two separate baths of the platinum anode and of the platinum cathode are joined by a ionic bridge supposed to equilibrate the global charge in each cell. The ECC sonde is fed with air by a whole teflon pump which minimizes the ozone loss in the input device. The different materials of the BM pump include plexiglas, metal, glue and lubricant which is certainly one of the most sensitive problem in this instrument and implies a long and careful preparation of the sonde. This is probably the origin of some uncontrolled reaction of this sonde when it is exposed to real atmosphere.

3. Data processing

3.1 Basis equation

The physical quantity measured by both the BM and ECC sensors is a current. The general form of the equation relating the ozone partial pressure P_{O3}[nbar] to the measured current i [μA] is (WMO, 1987; ENSCI, 1996):

$$P_{O_3}(z) = cst \cdot (i(z) - i_b) \cdot F \cdot T_p(z) \cdot E(z, T_p(z)) \qquad (1)$$

where:

- $cst = R/(2 \cdot e \cdot N_A) = 0,00431$ [nbar · dl / K · μA · s]
- R is the universal gas constant, e the elementary charge, N_A Avogadro's Number
- i(z) is the current [μA] measured at the altitude z
- i_b is the back-ground current [μA]
- F is the flow rate expressed as the time to pump 100 ml of air [s/dl]
- $T_p(z)$ is the pump temperature [K] at the altitude z
- $E(z,T_p(z))$ is the pump efficiency correction at the altitude z and a pump temp. $T_p(z)$

The terms i(z), $T_p(z)$ and $E(z,T_p(z))$ depend on the altitude z of the sonde while i_b is generally considered as constant. Instead of the altitude, pressure is also commonly used as vertical coordinate since it is a basic parameter measured by aerological sondes. The two scales are interchangeable as air temperature is also recorded.

Alternatives ways of processing the data as well as the differences between the processing of the two ozone sonde types are discussed in the SONDEX96 report (Stübi, 2001). In that report, the temperature dependence of the pump efficiency correction term, $E(z,T_p(z))$, was not considered. In the next paragraph, this additional temperature effect reported by De Backer et al. (1998) is discussed and its consequences on the data treatment is evaluated.

3.2 Temperature dependence of the pump efficiency

The efficiency of the ozonesondes pumps is decreasing as the pressure decreases at high altitude. In the data processing, the term E(z) (see equ. 1) corrects this problem. The Standard Operating Procedure (SOP) (WMO, 1987) for the BM sondes as well as the ECC manufactuor's recommendations (EN-SCI, 1996) prescribe a temperature independent term $E(z, T_p{=}cst)$. At Uccle (De Backer et al., 1998; De Backer, 1999), a sensitivity of that correction to the temperature of the pump has been measured in laboratory which is written in the above equation: $E(z, T_p(z))$. The result of their investigations is shown in fig. 1 as a linear dependence of the extra correction (multiplicative factor) in function of the altitude (~log(p)) and pump temperature.

Such temperature sensitivity is also present for the ECC sonde but the correction is approximately twice smaller for the ECC pumps than for the BM pumps.

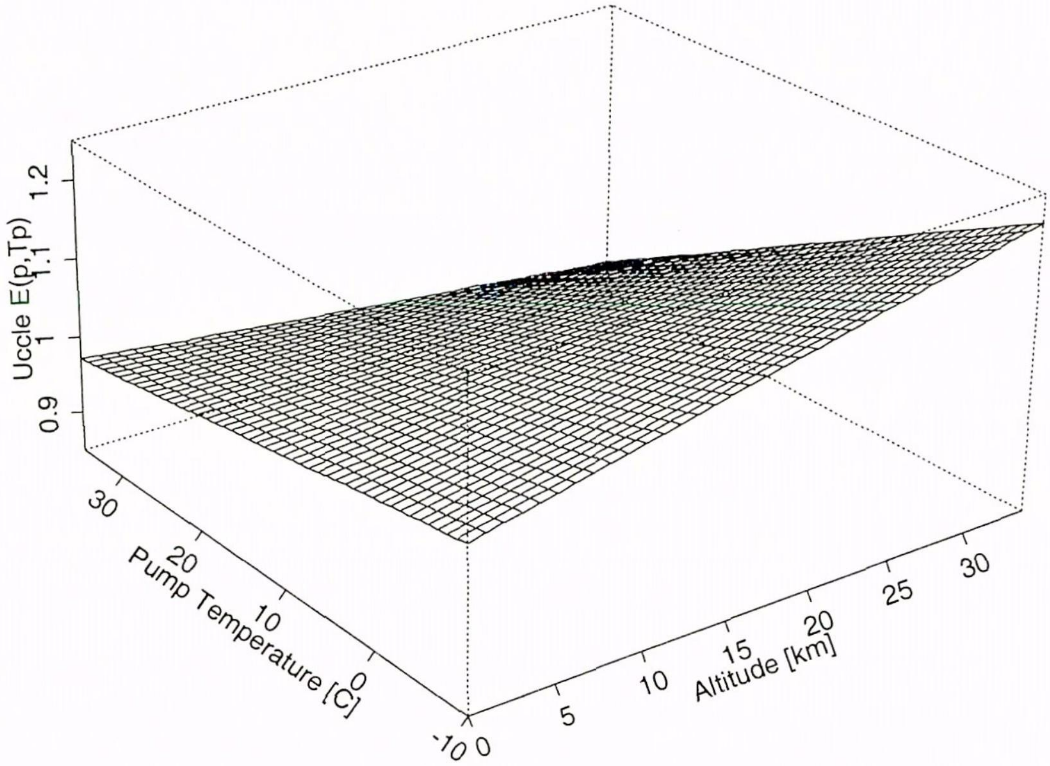


Fig. 1: *De Backer et al. (1998) extra pump efficiency correction for the BM ozonesondes as a function of the pump temperature and the altitude.*

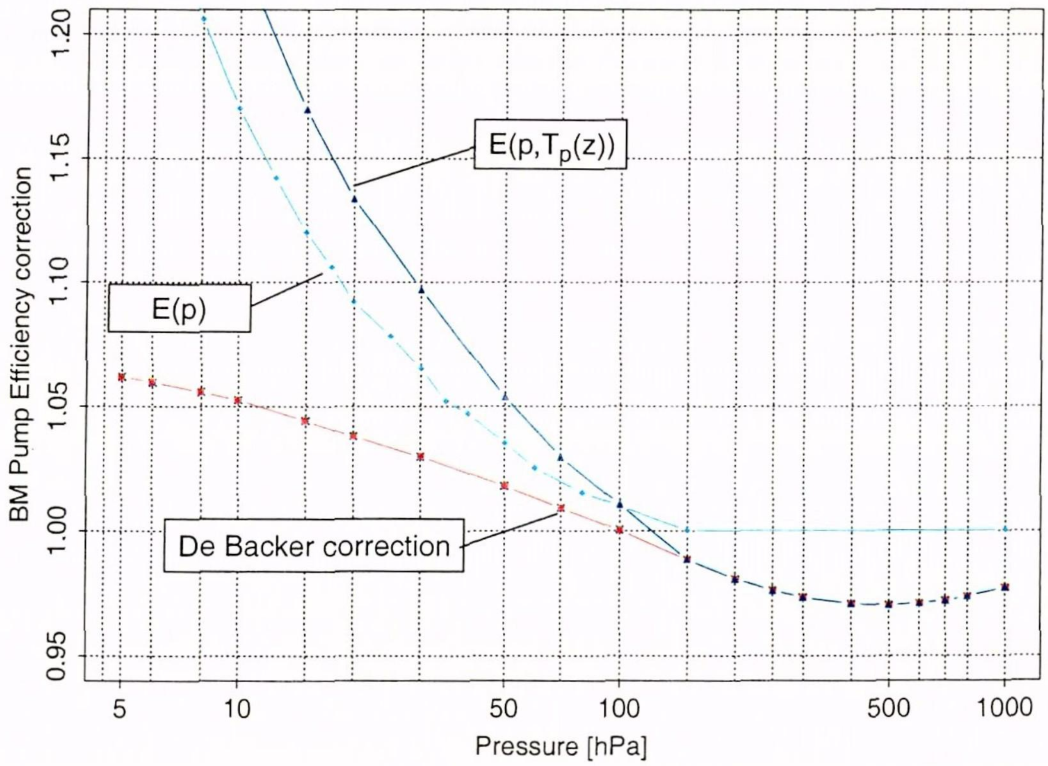


Fig. 2: *Pump efficiency correction for the BM ozonesondes. The **"De Backer correction"** superimposed to the standard **"E(p)"** correction results to the final correction **"E(p, T_p(z))"**. For notation, refer to "list of symbols" at p. 51.*

The temperature profiles used in De Backer et al., 1998 correspond to the so called box temperature which varies more during the ascent than the commonly used pump temperature. This means that the extra correction used to reprocessed the Uccle dataset is more important than the one for Payerne measuring conditions presented in fig. 2. The averaged temperature at the beginning of the ascent is ~ 33 °C and ~ 13 °C at the end. In comparison, the temperature profiles presented in De Backer et al., 1998 cover the range 25°C to -5°C. The De Backer extra correction applied to the Payerne conditions modifies the standard pump efficiency correction E(z) as reported in fig. 2. From the ground to ~ 100 hPa, the efficiency is in fact better then measured in the laboratory because of a higher pump temperature but at ~ 10hPa there is an extra +6% correction applied to the BM data.

The temperature dependent correction has been applied to the OZEX dataset of BM to compare it with the SOP treatment described in the SONDEX96 report. The average relative difference profiles is reported in fig. 3 with the reference series being the standard treatment including the Dobson scaling. Applying the temperature dependant efficiency correction generates the line marked ***De Backer***. The differences are at the two extremities of the profiles with a ~ -5% decrease of the ozone in the troposphere and a ~+3% increase at the top. For this ***De Backer*** difference profile, the temperature is only

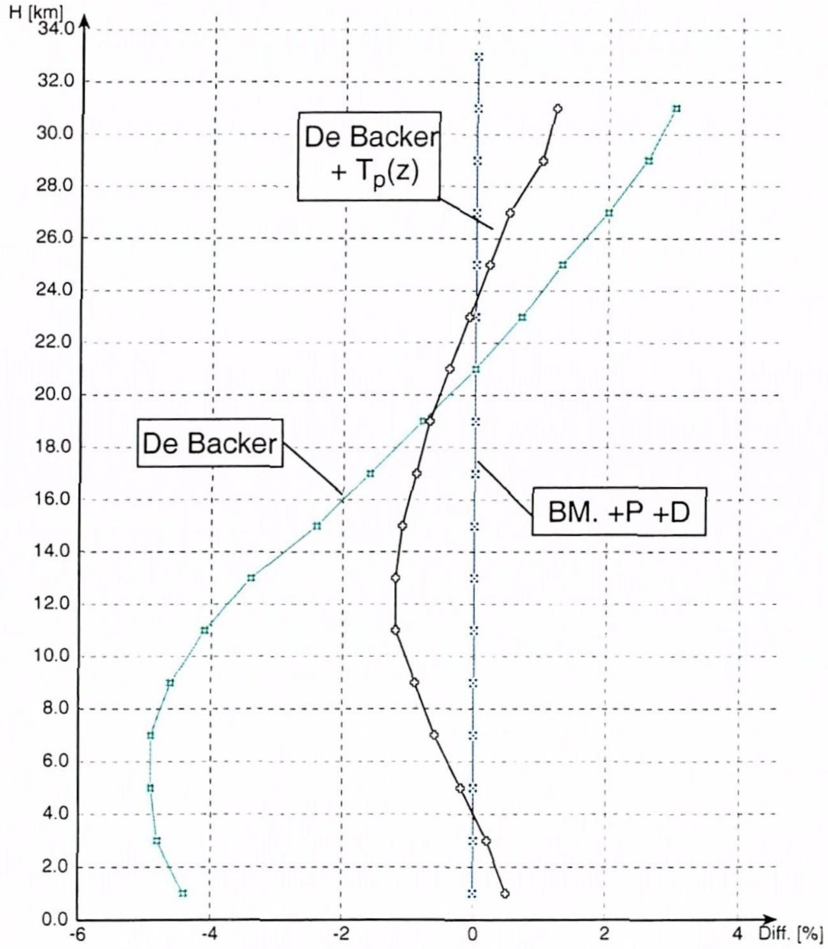


Fig. 3: Effect of the De Backer temperature dependence of the efficiency correction profile applied to the OZEX dataset. The three curves on the right are the equivalent to the ones on the left after scaling to Dobson ozone column. The scaling factors are reported above the arrows. For notation, refer to "list of symbols" at p. 51.

present in the pump efficiency correction term. But the pump temperature appears explicitly a second time in equ. 1 and it is fixed at T_p=280K according to the BM SOP. If a real temperature profile $T_p(z)$ is included in both places of equ. 1, the results is the curve marked ***De Backer + Tp(z)***. The differences are now confined to ±1% of the reference. The main differences are in the mean scaling factors: the standard processing gives f_c~1.09, adding solely the De Backer temperature correction reduces it to f_c~1.07 while having $T_p(z)$ in both places further decreases it to f_c~1.04.

In summary, it is certainly a difficulty to isolate the effects of the pump temperature in the final ozone values given by the BM ozonesondes. In the standard data processing of the BM, the simplest procedure (Stübi, 2001) is used which corresponds to disregard:

- i) the pump temperature profile by setting $T_p(z)$ = 280K

- ii) the residual ozone correction by setting i_b = 0

- iii) the temperature dependence of the pump efficiency correction by setting $E(z,T_p(z)) = E(z)$.

in equ. 1

In SONDEX96, it is shown that there is a compensating effects between i) and ii), while here a similar phenomena appears between i) and iii). Therefore, it is important to study the cumulative effects of these corrections by introducing them in the BM data processing and comparing the results to the ECC measurements. This study is reported in §4.

4. Results of BM - ECC comparisons

In this chapter, the relative difference profiles of the ozone measured by BM and ECC ozonesondes are presented in a similar form as in the SONDEX96 report (Stübi, 2001). Out of 96 dual flights, sixteen are not used for statistical analysis due to different reasons like loss of transmission over some parts of the soundings, low altitude burst of the balloon, calibration problems or breakdown of PTU sondes.

4.1 Overview of the results

In the results presented below, the difference profiles are plotted as a function of the altitude with the ECC data selected as the reference. In contrast to the previous SONDEX96 campaign, the mean scaling factor of the ECC sondes is significantly different from 1 namely 0.93. In opposite, the BM mean scaling factor is 1.09 which means that the two sonde types are more than 15% apart in term of total ozone column. The consequence is that the comparisons have to be done with the two datasets scaled to the Dobson column. Presently there is no explanation of the obvious overestimate of the ozone by the ECC sonde while any deficit can always be explained by uncompleted stochiometry or efficiency of the chemical reaction.

The overall picture that comes out of the OZEX campaign is summarized in fig. 4a by the ***BM+P+D*** line corresponding to the BM relative difference profile. In the troposphere and lower stratosphere, the difference is positive up to ~+7% close to the tropopause level, and gradually decreases to negative values, down to ~-4% at the top of the profile. This difference is obtained with the processing of the BM data as defined in the SOP (WMO, 1987; SONDEX96, 2001).

The other curves in fig. 4a illustrate the various steps of the data processing and their quantitative importance. They give the following information:

- the ***ECC+P*** line shows the effect of the Dobson scaling which on average decreases the data by -7%. This gives a mean scaling factor of f_c=0.93 for ECC sondes.
- the ***ECC*** and ***ECC+P*** line differ by the pump efficiency correction (Komhyr, 1986). The correction at 30 km is about 5.5%.
- similarly for the BM data, the ***BM*** and ***BM+P*** lines shows the pump efficiency correction according to Komhyr and Harris, 1965. The correction is applied above 13 km (150 hPa) and increases to about 11% at 30 km.
- the ***BM+P+D*** lines corresponds approximately to the ***BM+P*** line shifted to the right by the mean scaling factor of f_c=1.09. Due to the large deficit of ozone of the BM sondes in the upper part of the profile, a sign change occurs on the differences in the troposphere when the Dobson scaling is applied.

Figure 4b gives the standard deviations ([%]) associated with the various curves of fig. 4a. It demonstrates the variability of the BM data relative to ECC, notably in the troposphere and in the upper part of the sounding (above 25 km) where the ozone amounts

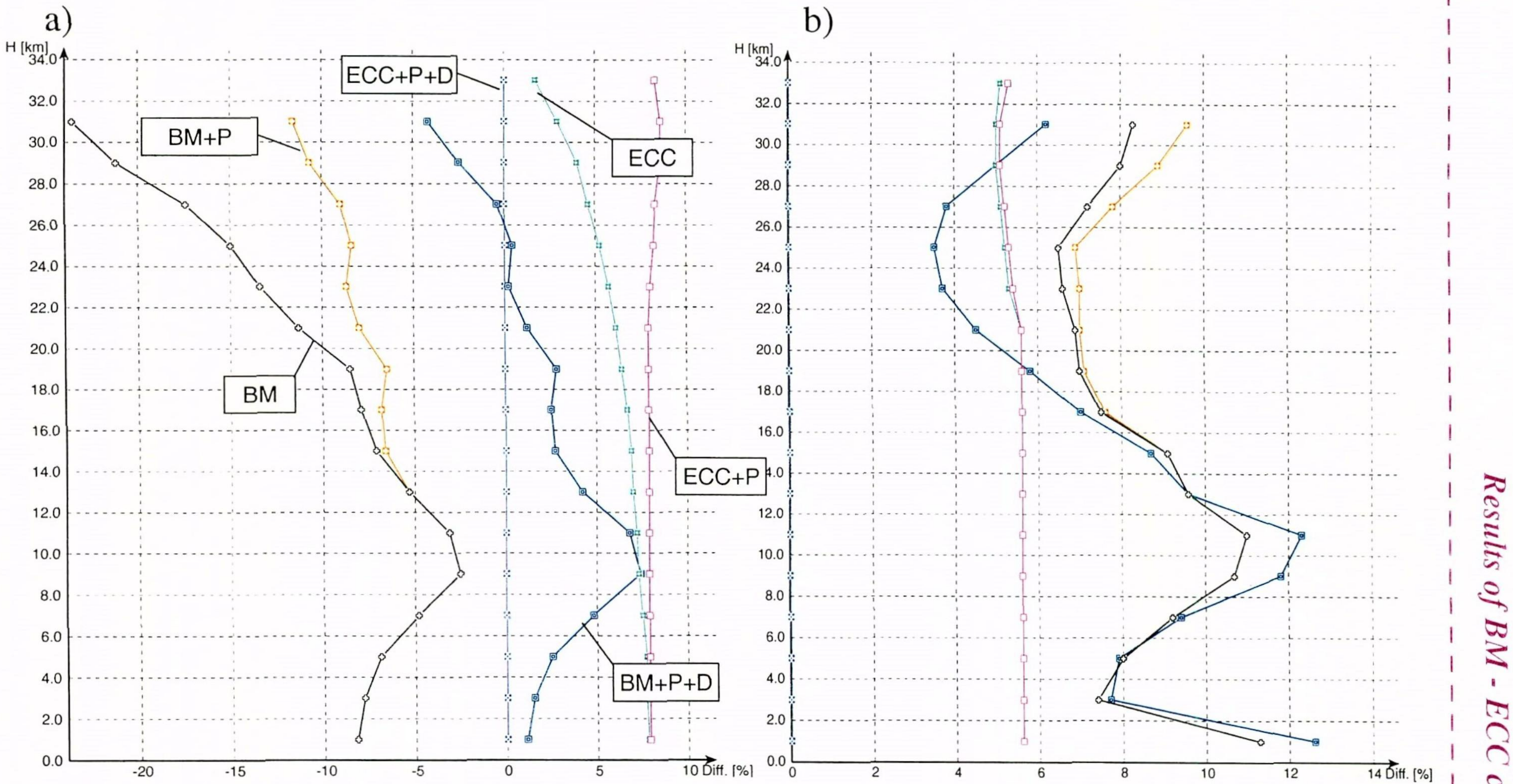


Fig. 4: (a) Relative Differences of the BM data compared to ECC with the following notation: "+P": Pump efficiency correction applied and "+D" Dobson scaling applied (For notation, refer to "list of symbols" at p. 51.); (b) Same as (a) for the standard deviation.

are small. The lowest point at 1 km include a large number of important discrepancies just after release of the balloon producing a peak in the standard deviations. The Dobson scaling diminishes significantly the standard deviations at the ozone layer altitude.

The present results can be compared to the SONDEX96 campaign (Stübi, 2001) which differs from OZEX campaign on following aspects:

- Shorter period, three weeks for SONDEX96 compared to one year for OZEX,
- Both ozonesonde types belong to the operational service,
- One ECC ozonesonde type (ENSCI) vs two in SONDEX96.

The two studies give a consistent picture of the differences between the BM and ECC ozonesonde (see fig 12a of SONDEX96 report). The large differences at the tropopause level appear on a wider range in OZEX which is expected due to the annual cycle of the tropopause height covered by this campaign. This cycle is probably also responsible for the larger standard deviations in the troposphere shown in fig. 4b compared to fig. 12b of SONDEX96 report. In the stratosphere, the difference at 31 km is smaller for OZEX, ~ -4%, compared to -8% for SONDEX96.

In the following paragraphs, the differences in the post-processing of the data are reconsidered in regard to their influence on the difference profiles presented in fig. 4a. An analogous analysis is reported in the SONDEX96 report and here, similar figures for the OZEX campaign are reproduced.

4.2 Background currents and pump temperature effects

In the troposphere, the ozone profile has low values with the consequence that the residual ozone generated by the background current is not negligible as discussed in the SONDEX96 report. The standard BM data processing doesn't include the residual ozone correction (i_b=0 in equ.1). The problem exists also for the pump temperature profile which is assumed constant ($T_p(z)$=cst in equ.1). These two parameters have been recorded recently during the operational BM soundings in Payerne. This allows to reprocess the BM data with these two parameters included and to compare them with the ECC data (see details in SONDEX96 report). In fig. 5, the difference profiles are shown with the ECC measurement (scaled to Dobson) as the reference. In the left panel, the full scale is presented and in the right panel a zoom on the troposphere with 500 m height resolution is given. The residual ozone correction on BM data has an impact in the troposphere (altitude < 12 km) by changing the linearly increasing positive differences (***SOP*** line) into an approximately constant negative (-5%) difference (***SOP+offset***). Conversely, the processing the BM data with a realistic pump temperature profile (***SOP+T_p(z)***) increases the difference, up to +12% at 10 km. If both corrections are superimposed (***SOP+offset+T_p(z)***), the differences profile reported in fig. 5 illustrates an improvement of the agreement between the two sondes, particularly in the troposphere where the differences are within ±2%.

In summary, introducing individually in the BM data processing the influence of the residual ozone correction and a realistic pump temperature profile, degrades the agreement between the two sondes. However, adding the two corrections together is benefi-

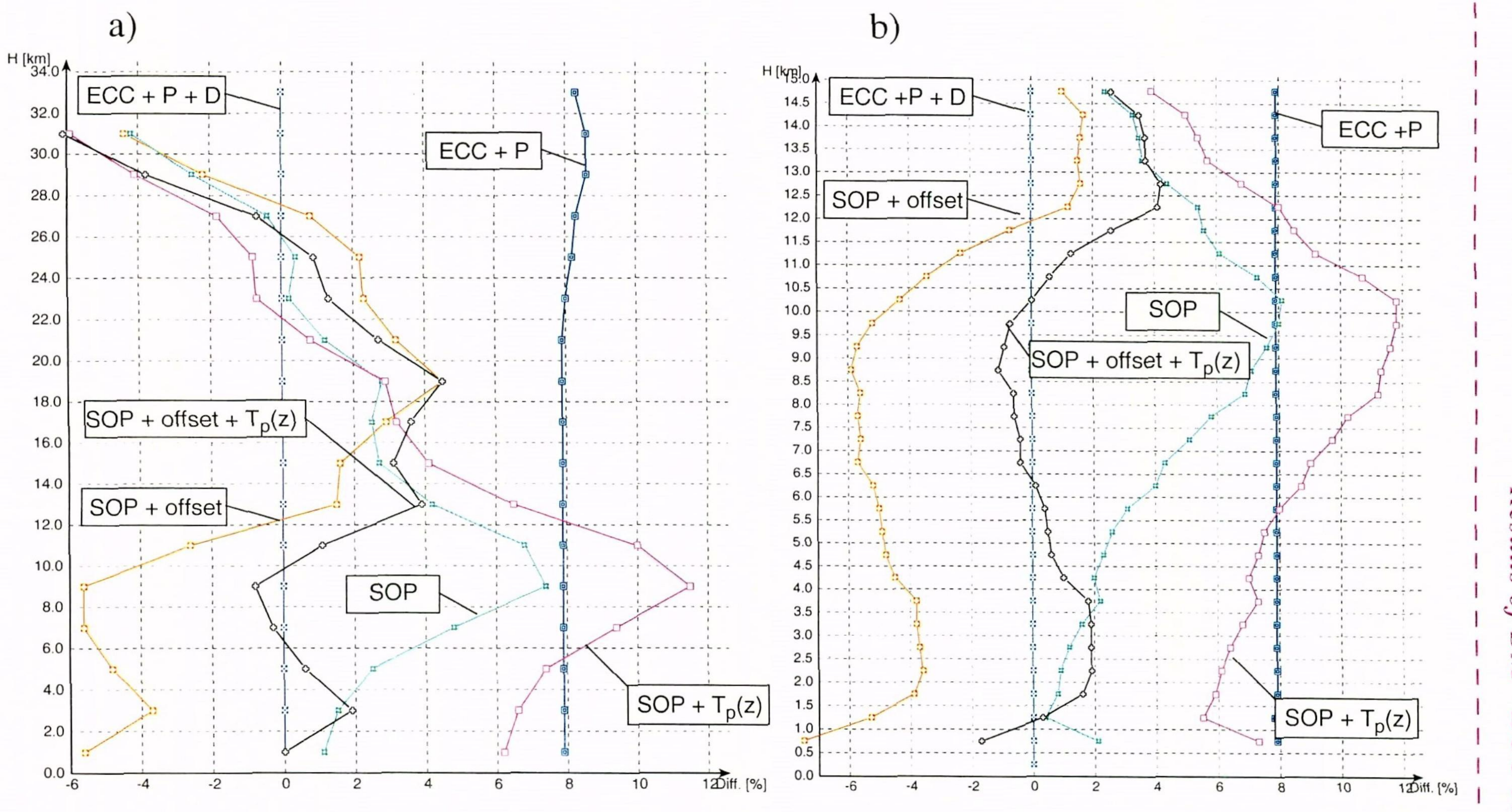
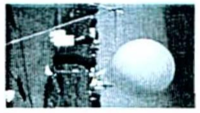


Fig. 5: Difference profile (BM-ECC)/ECC with emphasis on the residual ozone and pump temperature profile in the BM data processing. For notation, refer to "list of symbols" at p. 51. The (a)-panel show the entire profile up to 34 km while the (b)- panel is a zoom on the troposphere up to 15 km.



cial for the agreement between the BM and ECC sondes. These considerations applied mostly to the troposphere while the stratospheric part of the profiles are not much affected and the mismatch there is considered in the next section.

4.3 Pump efficiency correction for BM.

The major discrepancy between the ECC and BM is in the upper stratosphere which is currently thought to be a loss of the BM pump efficiency which is not fully compensated. As described in the SONDEX96 report, two alternatives for the BM pump correction profiles have been proposed by Steinbrecht et al., 1998. These two alternatives, denoted H1 and H2, are characterised by larger corrections at low pressure (see fig. 4 in SONDEX96 report).

Gathering the corrections of §4.2 ($T_p(z)$ and residual ozone) together with H1 or H2 result in the difference profiles between ECC and BM presented in fig. 6. The H1 cor-

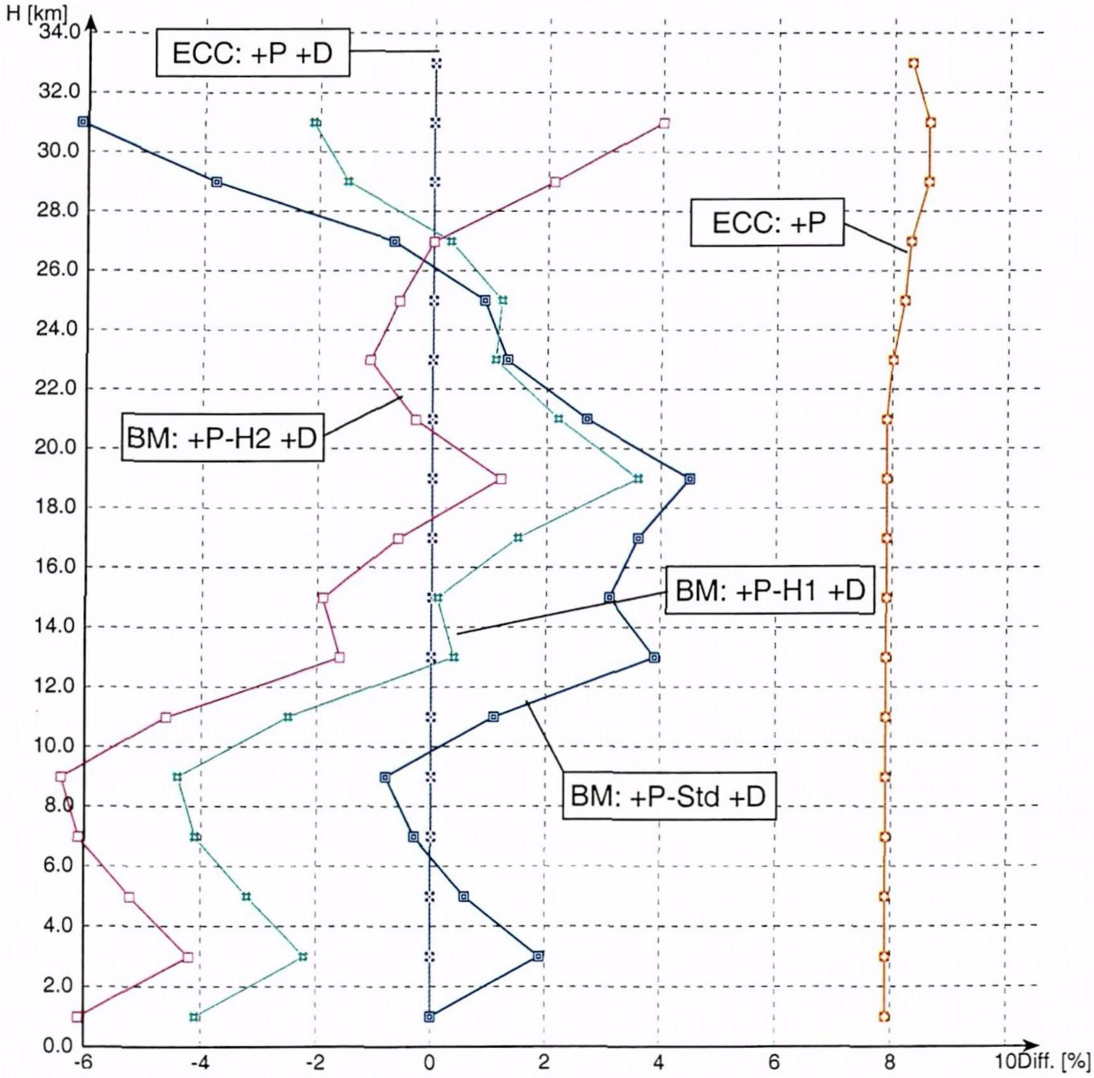


Fig. 6: Average difference profile (BM-ECC)/ECC for the BM data processing including a real pump temperature profile and a residual ozone correction, associated to three alternate pump efficiency corrections profiles: standard, H1 and H2. For notation, refer to "list of symbols" at p. 51.

rection (***BM: +P-H1 +D***) produces the best agreement with a difference within ± 4% of the normalised ECC data over the entire profile. The H2 correction (***BM: +P-H2 +D***) appears to over-correct the data at high altitude, inducing a larger difference in the troposphere. The standard correction (***BM: +P-std +D***) is similar to the one given in fig. 5. The mean scaling factors calculated for each of these BM series data are respectively f_c=1.10 for the standard pump correction, f_c=1.06 for the H1 and f_c=1.04 for H2.

In summary, even if H1 and H2 differ from the standard correction mainly for the higher points of the profile, they have a large influence on the entire difference profiles (fig. 6) because of the Dobson scaling. In SONDEX96 report, the best agreement between BM and ECC was found using H2. This was interpreted as a confirmation of Steinbrecht et al. results since H2 is an empirical adjustment of the BM measurements on other instruments. In the present study with other terms included in the BM processing, the H1 correction present a better agreement between the two sondes than H2.

4.4 Temperature dependant pump efficiency correction

As described in §3.2, the BM data can be processed in different ways regarding the

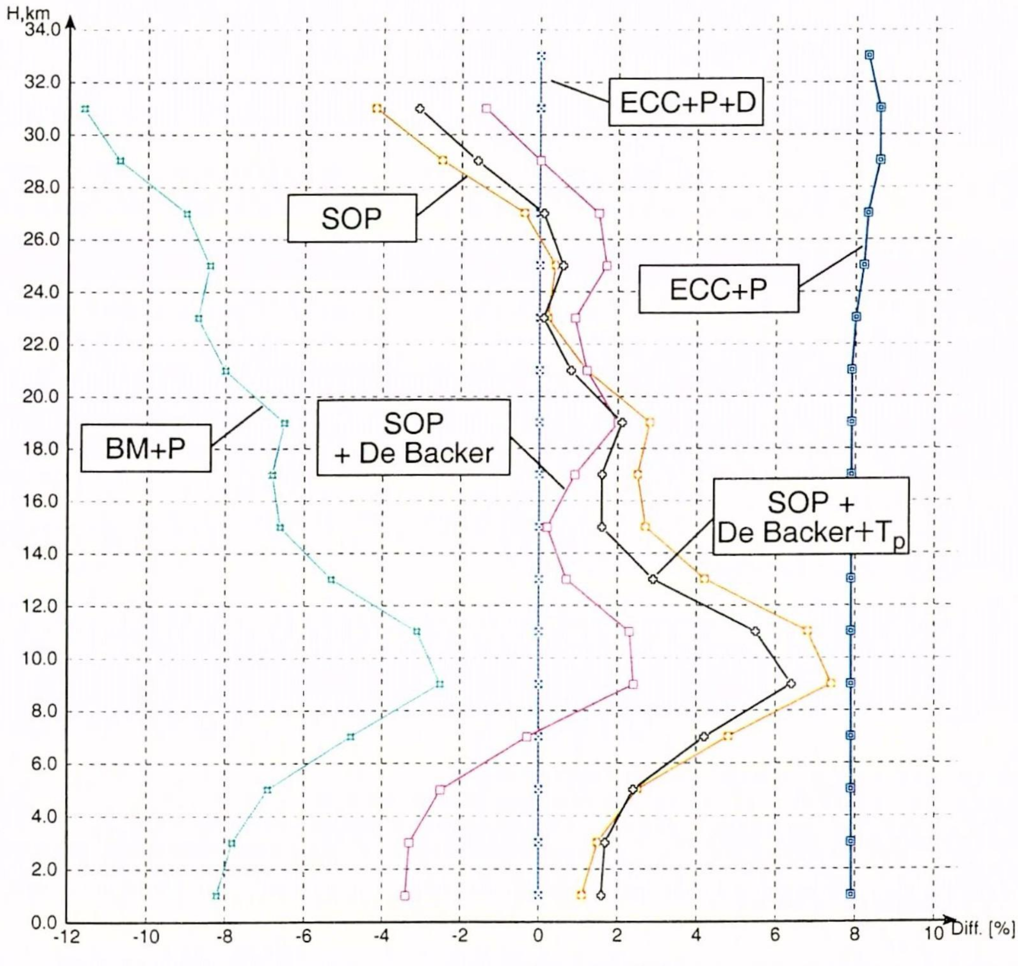


Fig. 7: Difference profiles BM-ECC/ECC for three different alternatives to incorporate the pump temperature (see text). The reference is the Dobson scaled ECC series. For notation, refer to "list of symbols" at p. 51.

pump temperature profile ($T_p(z)$) and the temperature dependence of the pump efficiency corrections, $E(z, T_p(z))$. Two alternatives to the SOP specifications for the BM data processing are considered here. Referring to the last two terms of equ. 1 (see §3.1), they appear like:

- SOP: $\ldots \cdot 280 \cdot E(z)$
- SOP + De Backer: $\ldots \cdot 280 \cdot E(z,T_p(z))$
- SOP + De Backer + T_p: $\ldots \cdot T_p(z) \cdot E(z,T_p(z))$

In fig. 7, the resulting difference profiles are shown in comparison to the ECC reference. This figure shows that if $T_p(z)$ is included solely in the De Backer correction (***SOP+ De Backer***), the agreement between the two sondes is indeed very good. Above 5 km, the difference profile is confined to ±2% and the correction factor decrease to f_c=1.05. This correction also establishes a negative difference in the troposphere, the BM measuring less ozone than the ECC. In the second alternative (***SOP+ De Backer +*** $\boldsymbol{T_p}$), the association of $T_p(z)$ in both terms produces a net effect of the order of 1% compared to the SOP treatment. In other words, introducing a real temperature profile in the two last terms of equ.1 is almost equivalent to setting a constant pump temperature for the whole profile.

In a final step, the third alternative above is applied respectively with the H1 and H2 pump correction curves. The resulting difference profiles are reported in fig. 8. With this combination, H1 gives a good agreement between BM and ECC with a difference profile within limited at ± 2.5%. The H2 case overestimates largely the ozone in the upper part of the profile while the standard correction produces a substantial positive difference from the ground up to 20 km.

4.5 Summary of BM - ECC comparisons

In summary, the BM and ECC data processing present two major differences: (i) the residual ozone or background current correction and (ii) the pump temperature profile. A third element is (iii) the temperature dependence of the pump efficiency correction. The term (ii) has a cancelling effect with one of (i) or (iii). Beside of that, different options for the pump efficiency correction (H1, H2, standard) profile have been published. In §4., different combinations of these elements have been included in the BM data processing and compared to the ECC results. If applying (i) and (ii) make sense, the net results of the comparability of BM and ECC sondes depend markedly on the pump efficiency correction term. Therefore a detailed study of the pump efficiency corrections and its temperature dependence would be worthwhile.

The problem of the measurement of the background current for the BM sonde has also to be addressed. There is no reference to it in the BM SOP and it can change depending on the moment it is measured in the preparation procedure.

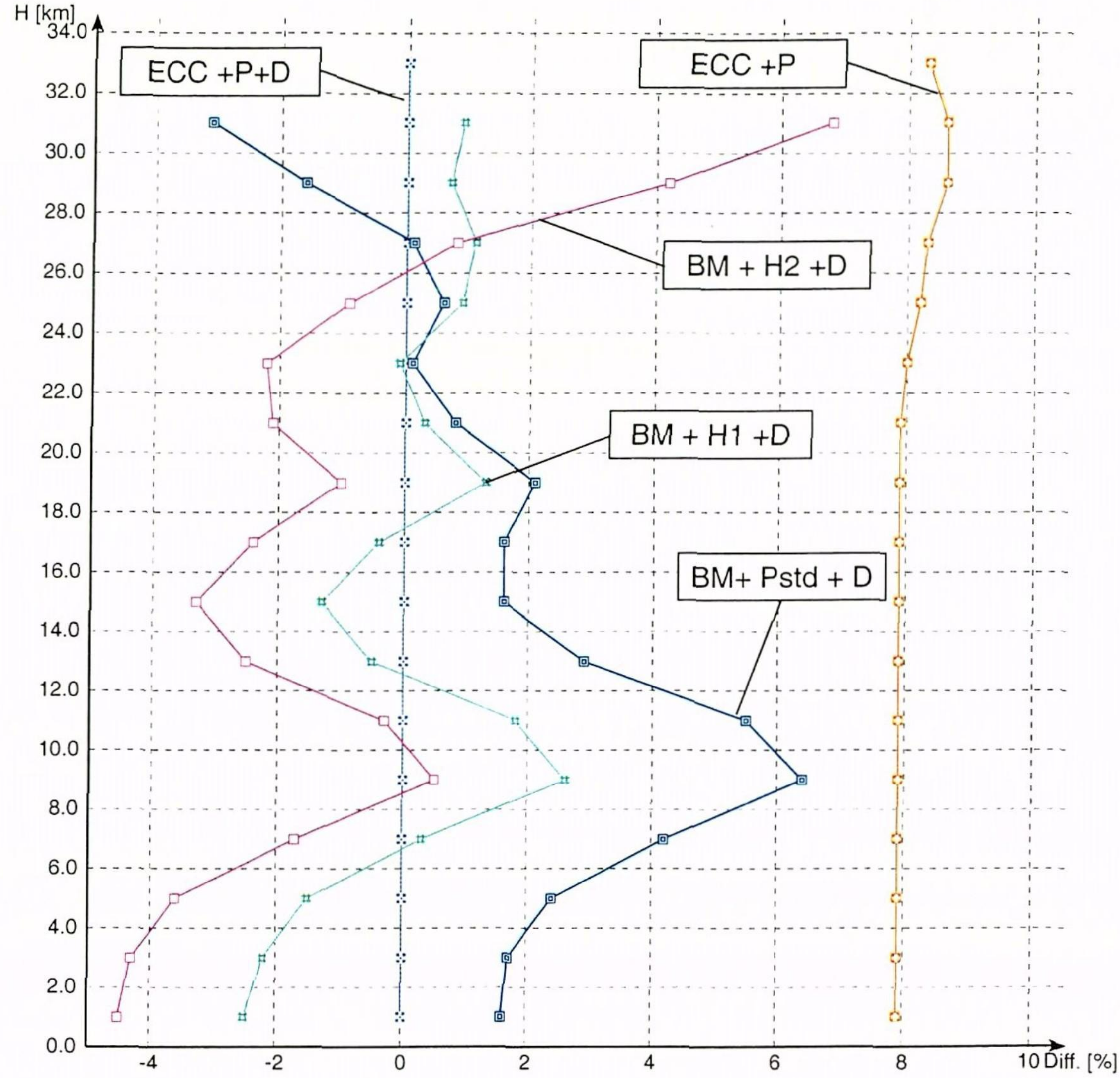


Fig. 8: Difference profiles between BM and ECC for the standard, H1 and H2 pump corrections profiles on the OZEX dataset. The processing includes the De Backer correction and a mean $T_p(z)$ profile. The reference being the scaled ECC serie. For notation, refer to "list of symbols" at p. 51.

5. Dual flights with the same sonde type

During the OZEX campaign, dual flights with two ozonesondes of the same type have been performed for a total of nine BM-BM and six ECC-ECC flights. The goal is the evaluation of the relative reproducibility of the two systems, taking into account the fact that no reference is available.

5.1 The scaling factors

In fig. 9 the scaling factor of the various dual flights are presented with an arbitrary x-axis scale (flight number) which is crudely a time scale. The good reproducibility of the ECC sondes is seen in this picture by the fact that the scaling factors within each pairs are close to each other within ~2%. In contrast, the BM pairs show scaling factors with a mean difference of ~10%. Averaged values for both sonde types are shown by the horizontal coloured lines.

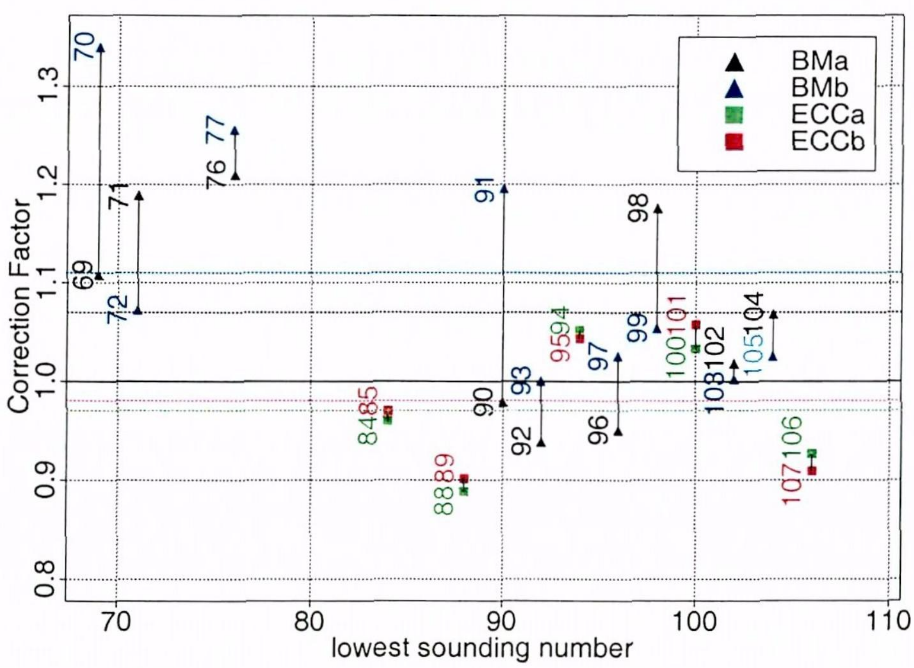


Fig. 9: Correction factors of the dual BM-BM soundings (black and blue) and between the dual ECC-ECC soundings (red and green).

5.2 BM - BM Dual flights

The BM-BM dual flights have given results of two types, the first one, shown in fig. 10, represents a very good agreement between the two BM sondes after scaling to the Dobson column. The difference profiles given on the right panel is not illustrative of typical BM-BM results but it is more representative of ECC-ECC results. The differences are of the order of 2 nbar which is particularly good.

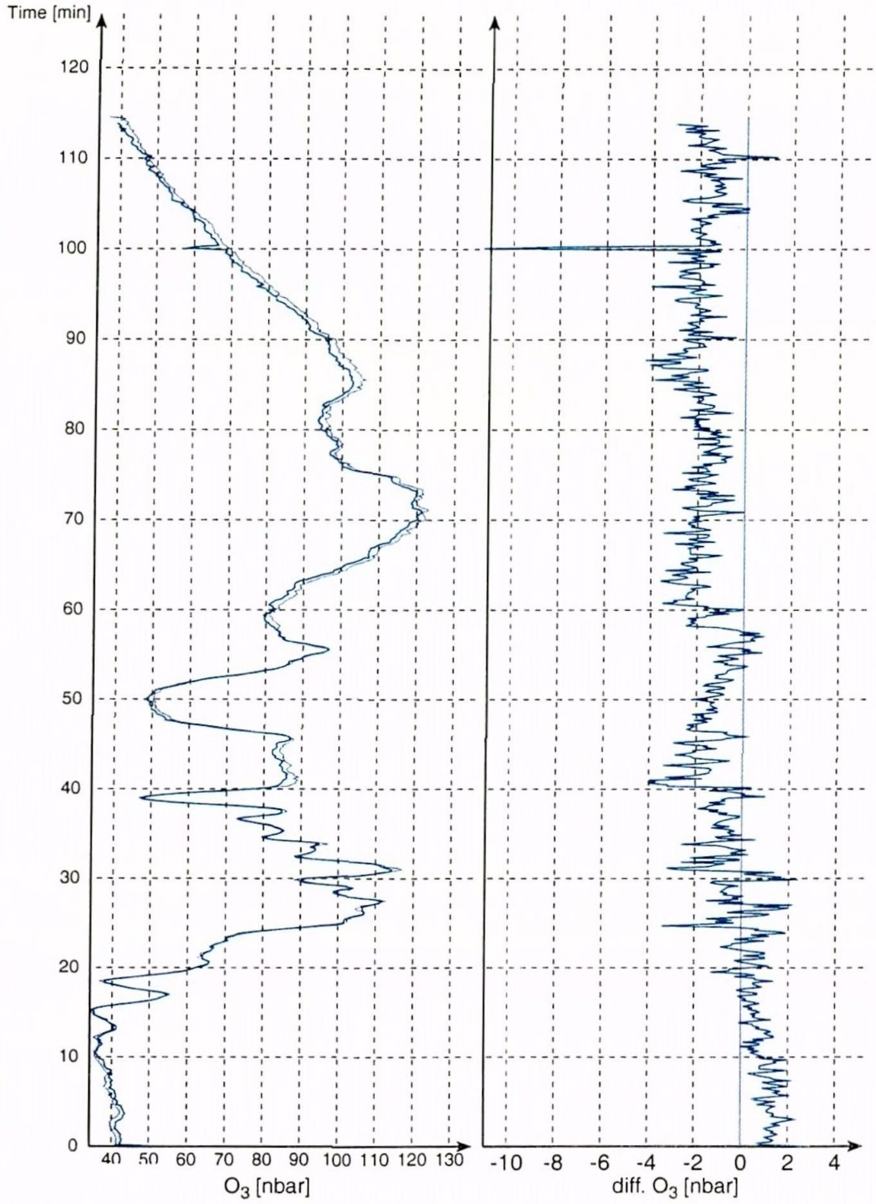


Fig. 10: Dual BM-BM sounding showing a good agreement between the two BM sondes. On the left panel, the ozone profile ([nbar]) is reported again time ([min]). On the right panel, the difference profile is plotted with the same units.

A more common picture of the BM-BM results is given in fig. 11 where the differences are larger of the order of a few nbar, and the difference profile presents some similarity to the ozone profile. This effect is interpreted as a correction, induced by the scaling to the ozone column, which is not strictly proportional to the ozone amount but from other side effect. In the case presented in fig. 11, it appears that the two sondes behave similarly up to about half of the ascent and higher up there is a systematic drift of one sonde compared to the other. The discrepancy is (over-) compensated by a scaling factor which is too high (or too low) in the sonde which behaves badly and this generates a difference profile which contain a (visible) fraction of the ozone profile. This effect is absent in fig. 10 where the difference profile doesn't show a remnant of the ozone profile. In the analysis of the BM-ECC dataset, the difference profiles frequently displays a similarity to the original ozone profile. Presently, except the Uccle treatment (see SONDEX96 report) no alternative scaling have been proposed but this point will certainly be addressed in the future.

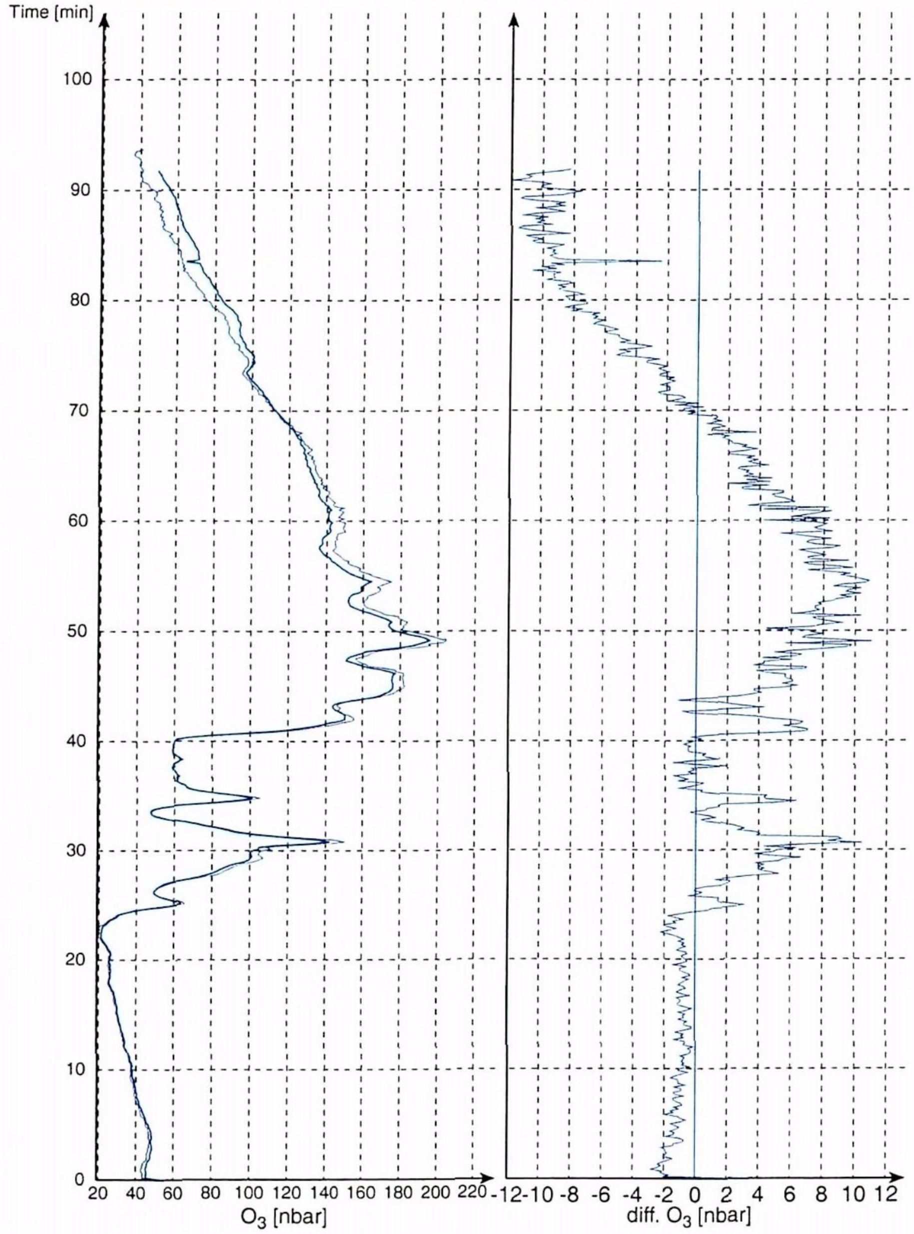


Fig. 11: Example of a dual BM-BM sounding presenting larger difference then the fig. 10. The difference profile shows the signature of the ozone profile. The scaling of the data to Dobson column is responsible of that effect (see text).

The dual flights of the same type give only a crude estimate of the reproducibility of the two sonde types because of the small flights sample. In fig. 12, the RMS difference profiles for the BM ozonesondes is given in ozone pressure [nbar] and in relative units [%] with the same x-axis. The use of an RMS error is necessary in absence of reference, the two sondes being of the same type, there is no reason to select one as the reference. The absolute difference profile is ~ 4 nbar without having a well defined shape. The corresponding relative profile is given for the data before and after scaling to the Dobson column. These profiles have the larger values of >10% in the low ozone environment of the troposphere and typical 4% - 6% differences in the stratosphere. The scaling to the Dobson gives an average significant improvement of ~2% over the entire profile. The corresponding picture for the ECC dual flights is given in fig. 13. In this case only the relative profile corresponding to the scaled data is presented because the Dobson scaling for the ECC sondes doesn't significantly change the RMS difference. The major differences of the RMS profiles between the two ozonesondes are found in the tropo-

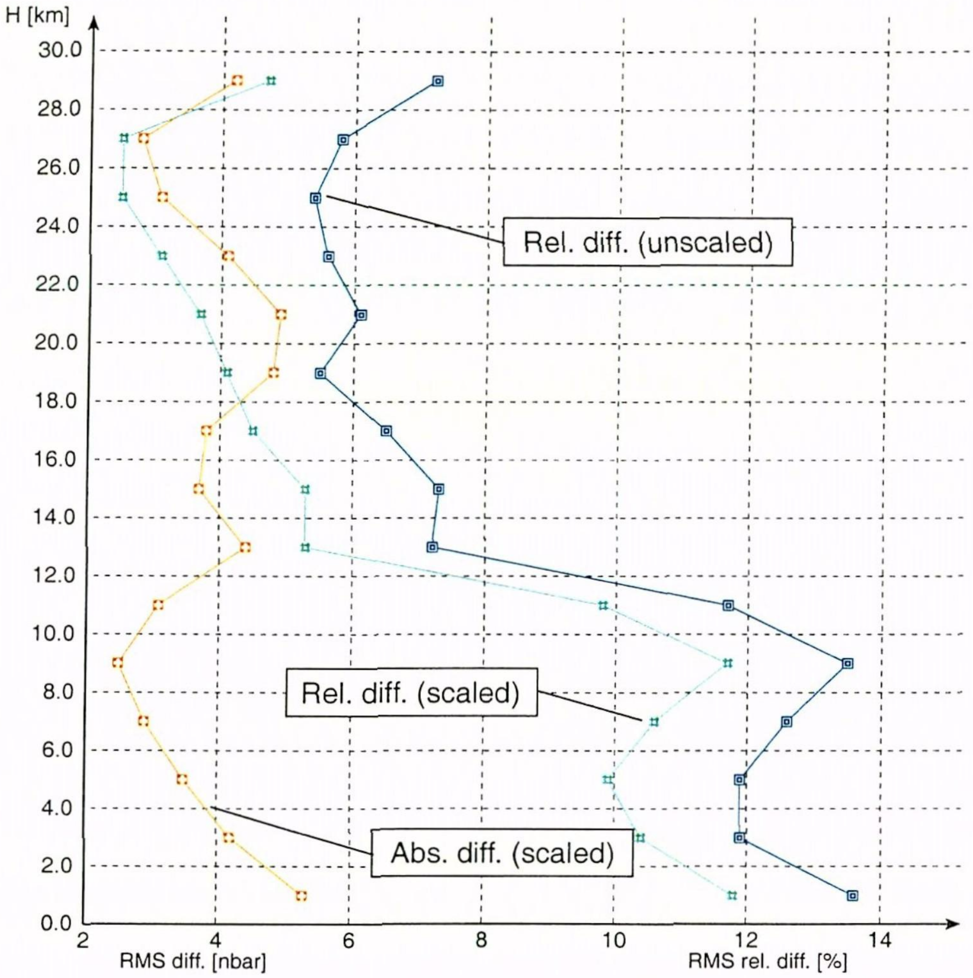


Fig. 12: Average RMS difference for nine dual BM-BM soundings. The x-axis is in [nbar] for the absolute RMS difference profile, respectively in [%] for the relative RMS difference.

sphere and in the upper part of the profile where the values are about twice larger for the BM sondes. In the range of 15 to 20 km, the RMS difference are of the same order of magnitude for the two sonde types.

In summary, the dual flights of two BM, resp. two ECC ozone sondes has allowed to estimate of the variability of the two tested ozonesondes: nine dual BM flights produce an averaged 4 nbar ozone RMS difference which is about 10% in the troposphere and 4% in the stratosphere. Six dual ECC flights show an RMS difference around 2 nbar at low, resp. high altitude and around 4 nbar in the region of the maximum of ozone. The Dobson scaling does improve the RMS differences for the BM sondes but doesn't change the RMS differences of the ECC sondes.

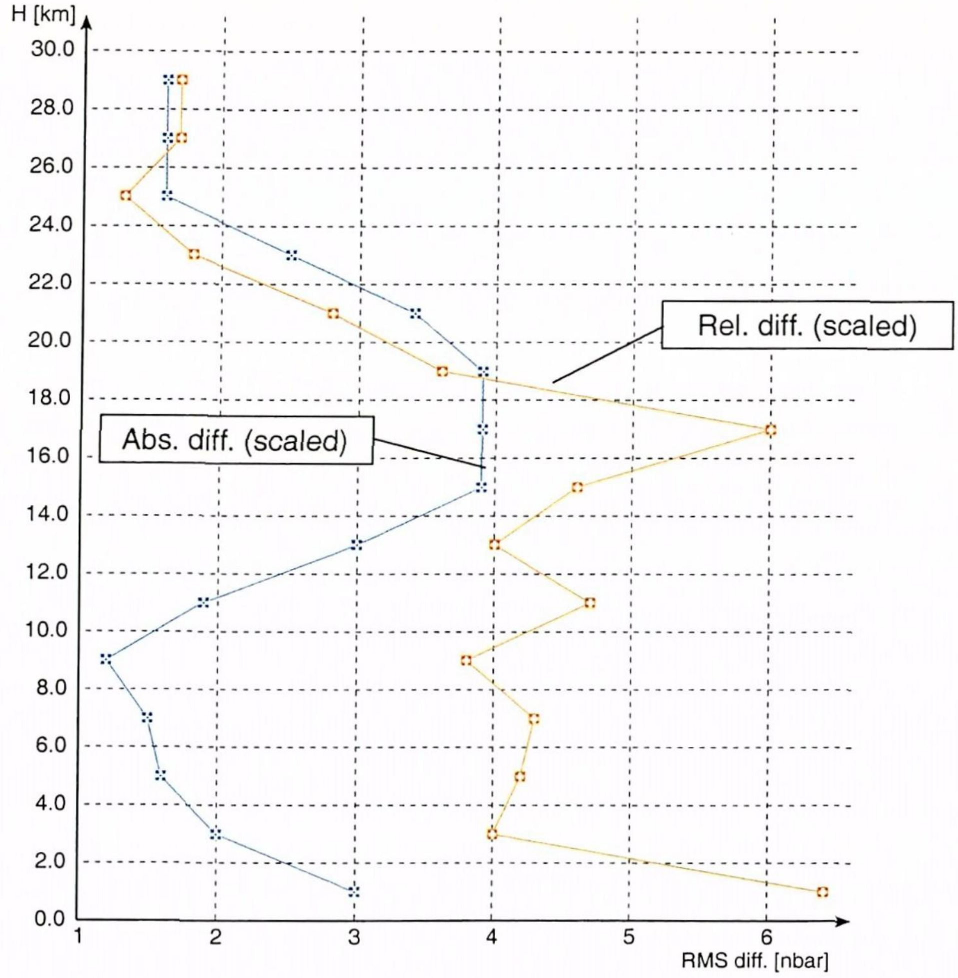


Fig. 13: Average RMS difference for six dual ECC-ECC soundings. The x-axis is in [nbar] for the absolute RMS difference profile, respectively in [%] for the relative RMS difference. The data have been scaled to the Dobson for that figure.

6. Trend dependency on the sonde type

As a first attempt to simulate the introduction of the ECC ozonesonde as the operational instrument, we have evaluated the trends of the ozone on a set of pressure levels, under different circumstances:

- With the operational BM time series between January 1995 and June 1999.
- With the operational BM time series between January 1995 and March 1998 and the BM OZEX time series between April 1998 and June 1999.
- With the operational BM time series between January 1995 and March 1998 and the ECC OZEX time series between April 1998 and June 1999.

The values at a given pressure level are interpolated linearly between the two adjacent measurements and monthly averages are calculated. Then the time series are deseasonalized. This operation consists in subtracting to each value the average of all the values established for the same month of each year. A linear regression of the deseasonalized time series explicitly gives the trends. This method is illustrated in fig. 14 for the 50 hPa pressure level. It appears from the calculation that the change of sondes produces a smaller affect then the change of sample size used for the trend calculation. In other words, considering a sample of 1 flight/week (OZEX) compared to 3 flights/week (operational) has a larger impact than considering BM data vs ECC data.

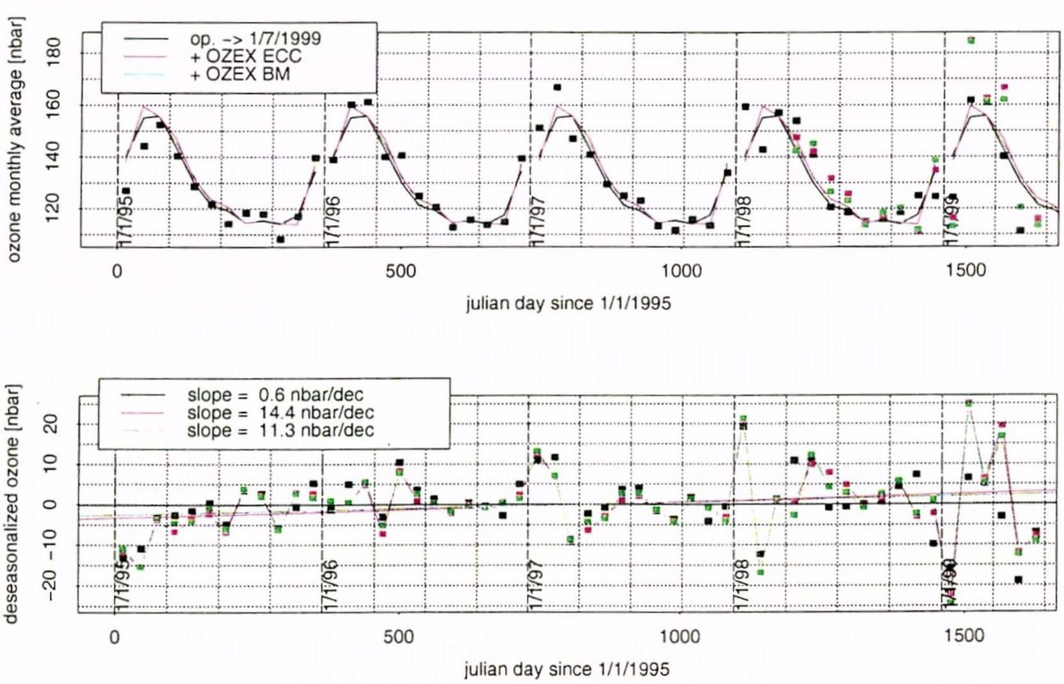


Fig. 14: Illustration of the effect of the change from BM to ECC sonde on the ozone trend at 50 hPa. Top panel: monthly average of measured ozone for the operational series since 1995 to June 1999 (black squares), with replacement by OZEX BM sonde measurements (green squares), and by OZEX ECC sonde measurements (pink squares) between April 1998 and June 1999, with respective seasonal cycle. Bottom panel: deseasonalized values with a trend slope in nbar/decade for each case.

The trends as a function of different pressure levels are summarized in fig. 15. One should be aware that the values of the trend given here are evaluated on a 4 years period and cannot be directly compared to the long term trends. For instance, the ozone long term trends in the stratosphere have negative values of the order of -3% while the numbers quoted here are positive and much larger. But also, due to the numerous dismissed dual flights, the monthly mean values are occasionally reduced to a single flight! For most of the levels considered in fig. 15, the conclusion reach for the 50 hPa holds, stressing the problem of the sample size. The two lower pressure levels present significant differences between the ECC and BM OZEX sub-samples. This is expected considering the differences observed between the two sondes at the upper part of the profiles as discussed in §4.

In a second step, an empirical correction (black box) is used to artificially stress the mean ECC values on the BM ones. Two such black box corrections have been selected: the first one has been computed from the SONDEX96 campaign difference profile (std black box) and the second from the OZEX difference profile (ad hoc black box).

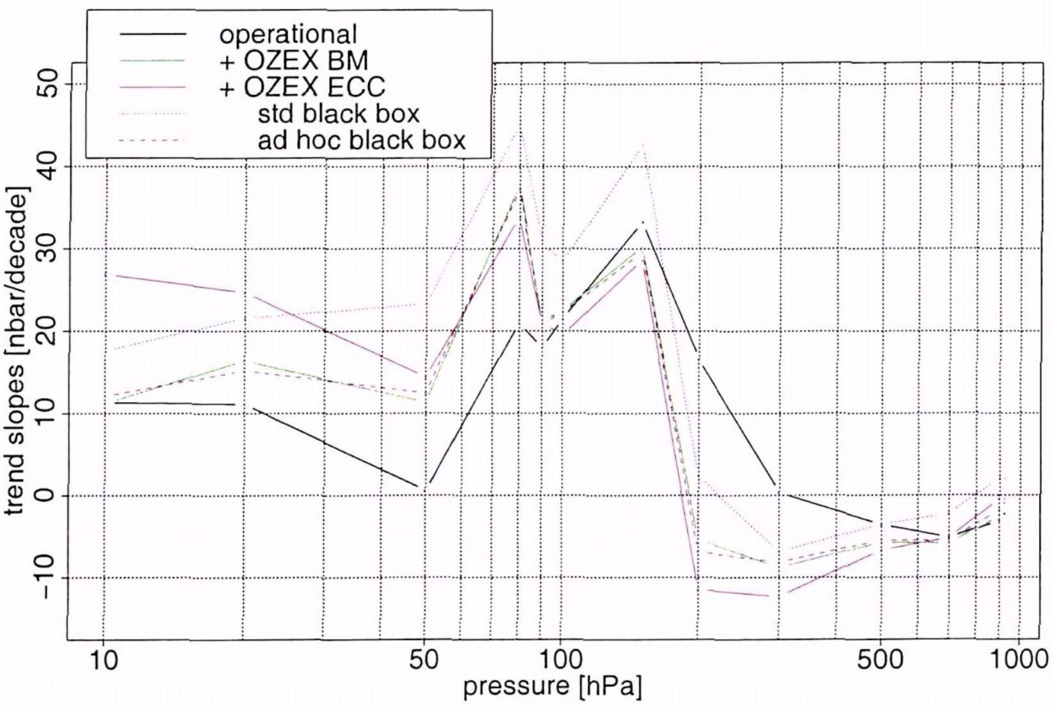


Fig. 15: Trend slopes with respect to the pressure for the operational series since 1/1/1995 (black line), when the operational series is replaced by the BM OZEX subsample (green curve) or by the ECC OZEX subsample (pink line) since 1/4/1998. The dashed and dotted lines are obtained after correction of the ECC values with two different black boxes.

As shown in fig. 15, the conformity between the two OZEX trends has deteriorated using the SONDEX96 correction while the *ad hoc* correction produces a good adequacy between the BM and ECC OZEX trend estimations. Therefore, it appears that the short term SONDEX96 campaign delivers a mean difference profile which cannot be used to correct the OZEX campaign data blindly. Time scale, preparation procedure, ECC sonde types are some of the factors which could explained the difference between the campaigns.

7. Conclusion

The OZEX comparison project was a part of the ongoing activities to improve the ozone sounding measurement technique. It had two majors aims, firstly to ascertain the comparability of the BM and ECC sondes and confirm the SONDEX96 results. Secondly, to evaluate the consequences on the trends of a hypothetical change of BM to ECC sonde as operational instruments at Payerne.

For the first aim, the relative difference profile between BM and ECC ozone measurements given in fig. 4 shows that the difference is smaller then ±5% except for the tropopause level where it is +7%. It is however necessary to scale both sondes data on the Dobson total ozone column to achieve this results. The OZEX results confirm the difference profile observed in the SONDE96 campaign. The major difference is found in the average scaling factor of the ECC data: for OZEX, the mean factor is 0.93 while for SONDEX96, it is 0.98. Therefore, the comparisons have been done between scaled data for both sondes in the OZEX case.

Various alternatives to the standard data processing of the BM ozonesonde have been tested to evaluate their influence on the difference profile. One alternative is an adaptation of the BM data processing to have a similar treatment for both sondes (§4.2). Another one is equivalent to the treatment used at the Uccle station to homogenize their transition from BM to ECC ozonesonde in 1997 (§4.4). A third alternative was used at the Hohenpeissenberg station to homogenize the ozone profiles from different instruments (§4.3). It is difficult to classify these processings since all exhibit advantages and disadvantages as discussed in this report. The best agreement is illustrated in fig 8 where the differences are within ±3%.

For the second aim, a simple trend analysis evinced the fact that the difference in the sample size (1 vs 3 soundings per week) have a larger influence than the sonde considered (BM vs ECC). With a similar sample size for the two sondes and the SOP BM treatment, the trend are different only at the uppermost altitude. A correction have to be applied to correct that discrepancy.

The OZEX project pointed out the importance of the following questions which have to be addressed:

- scaling factor of ECC data: in general, the scaling factor are lower than one. An in-depth understanding of the ECC behaviour is still missing,
- the pump efficiency correction profile: on the one hand, the laboratory measurements disagree on the pump efficiency correction profiles and, on the other hand, the temperature sensitivity of those corrections has not been studied properly,
- the Dobson scaling is a crude method which certainly failed in some cases. Since it is a necessary operation for the BM ozonesonde, other alternatives should be tested.
- the background current for the BM sondes: it is not defined in the SOP since it is not used in the data processing. If it is necessary to reprocess the data, it has to be properly chosen in the metadata accompanying the past and present BM soundings.

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