CLIMATOLOGY OF THE MIDDLE ATMOSPHERIC TEMPERATURE OBTAINED FROM LIDAR MEASUREMENTS Al MID- ANI) LOW-LATITTUDES.

1. Climatological average and two-day to two-year variability.

Abstract

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1. Introduction

The middle atmospheric temperature structure has been studied for several decades now. It started with rocketsondes measurements, providing temperature profiles up to 60 km but with relatively poor accuracy [Schmidlin, 1981], and Falling spheres allowing reaching 90 km of altitude, Elterman [1951] had the idea to measure density using Rayleigh backscattering by the atmospheric molecules, then came the first temperature measurements derived from lidar measurements of the middle atmospheric relative density [Hauchecorne and Chanin, 1980], providing better vertical resolution and accuracy. Unfortunately, for all ground-based methods cited above the measurements were located above lands in the northern mid-latitudes. The crucial need for a better horizontal coverage, especially for low-latitudes, ocean areas, and southern hemisphere, led to the development of satellite measurements. The Pressure Modulated Radiometer (PMR) (Curtis et al., 1974] in the seventies, the Limb Infrared Mesospheric Sounder (LIMS) [Gille et al., 1984], the Stratospheric Aud Mesospheric Sounder (SAMS) [Rodgers et al., 1984], the Stratospheric Sounding l-huts (SSU) [Miller et al., 1980], and the Solar Mesosphere Explorer [Clancy and Rusch, 1989] in the eighties obtained successively a global coverage of the middle atmospheric temperature profiles. However, the vertical resolution remains poor compared to most of the ground-based instruments. More recently, the Upper Atmosphere Research Satellite (UARS), launched in September 1991 and especially dedicated to the study of the middle atmosphere allowed measuring the stratospheric and lower mesospheric temperature using 4 instruments: the Microwave Limb Sounder (MLS) [Fishbein et al., 1996], the Cryogenic Limb Army Etalon Spectrometer (CLAES) [Gille, 1996], the Halogen Occultation Experiment (HALOE) [Russell et al., 1996], and the Improved Stratospheric And Mesospheric Sounder (ISAMS) [Taylor et al., 1996]. Some of these instruments are still operating at this date, giving one of the most extensive satellite data set ever obtained, though with still a poor vertical resolution associated with the remote passive sensing methods used.

In contrast, the lidar measurements remain of best vertical resolution and accuracy. Therefore, they make it very suitable for studying variations of the middle atmospheric temperature at various time scales. This paper will describe the middle atmospheric temperature climatology from lidar measurements obtained at several mid- and low-latitudes locations. Two Rayleigh Mars of the Service d' Aéronomie du CNRS, France (44°N), the two Rayleigh lidars of the NASA-Jet Propulsion Laboratory, US (34.4°N and 19.5°N), and the Na Lidar of Colorado State University at Fort Collins, US (40.5°N) were used to perform this climatology. After a short technical description of the instruments and description ot" the data sets, the data processing and associated results are presented These include climatological temperature average through the year, annual and semi-,mmual components, 2- to 33-days variability, departure from the climatological model CIRA-86, comparison between instruments and identification of the Quasi-Biennial Oscillation. The overall data set extends from 1978 to 1997, with different period of measurements depending on the instrument. The long-term trend, the planetary wave activity, the effects of volcanic eruptions (Pinatubo, 1991) and 1 l-years solar cycle, and the mesospheric temperature inversions are not described here, They are studied separately in different papers, using the same lidar database.

**** Reference Keckhut trends 1998 ****
**** Reference She Pinatubo 1998 ****
*** * Reference Hauchecorne Planetary waves 1998 ****
*** * Reference Leblanc Inversions 1998 * ***

2 Lidar description

Rayleigh scattering:

Laser radiation emitted from the ground at wavelength λ and transmitted into the atmosphere is backscattered by molecules in the. atmosphere and collected on the ground by a telescope When the Mie scattering due to the aerosols particles is negligible compared to the molecular scattering (i.e. above 30 km) the number of photons received from a scattering layer δz, at a mean altitude z, is proportional to the number of photons emitted in the laser pulse and to the number of air molecule.s (or air density). If the backscattering process is Rayleigh scattering then the transmitted and received wavelengths are the same

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and, assuming that the only non-negligible absorption in the atmosphere is due to ozone, the atmospheric density cart be derived from the Rayleigh lidar equation and written:

$$\rho(z) = N(z)\,K\,\frac{(z - z_0)^2}{\delta z}\exp\left(2\tau_{Ray}(\lambda,z) + 2\tau_{O_3}(\lambda,z)\right) - \text{‘}(z) \qquad (1)$$

where $N(z)$ is the number of photons received, per laser pulse, from altitude z by a telescope at altitude z_0. $\tau_{ray}(z)$ and $\tau_{O3}(z)$ are the optical thickness integrals for the Rayleigh extinction and the ozone absorption between the altitudes z_0 and z. K is an undetermined proportionality constant dependent on instrumental parameters n(z), is the number of photons coming from the natural sky background light added to the photonic and electronic noise coming from the counting system The received, backscattered radiation can be detected and measured using a photon counting system comprising a photomultiplier, pulse height discriminator and a multi-channel-scaler (MCS). At high count rates the response of the counting system becomes non-linear, due to pulse pile-up duration effects, and a correction has to be applied in order to obtain the true number of photons received from the observed number of photons counted. In addition, to reduce the sky background noise to its minimum, the lidar measurements are usually performed at night- In some exceptions and with high performance optical components, daytime measurements are possible, but since the best accuracy is required for this study, they are not used here.

After ext.meting the noise, the temperature is deduced from the relative density using the classical hydrostatic balance and perfect gas law assumptions [Hauchecorne and Chanin, 1980]:

$$T(z_i) = \frac{1}{\rho(z_i)}\left[\rho_{top}T_{top} + \frac{Mg(z_i)\delta z}{k}\sum_{z_i}^{z_{top}-1}\rho\left(z_i + \delta z/2\right)g\left(z_i + \delta z/2\right)\right]$$

M is the air molecular mms, k the Boltzmann constant and g(z) the gravity. ρ_{top} and T_{top} are “a priori’ values of density and temperature at the top of the profile. Such a priori information is typically taken from climatological models like CIRA-86. The total error on temperature at the top can be larger than 20 K but it rapidly decreases as the temperature profile is integrated downward (divided by 3 10 km below the top), Following equations (1) and (2), the unknown constant K is suppressed since the temperature derivation depends only on the relative density, i.e. the ratio of the absolute density at two successive. altitudes.

Raman-vibration Scattering:

In contrast with the Rayleigh scattering, the Raman scattering is inelastic and corresponds to a change in the vibrational state of the Nitrogen molecule. The backscattered wavelength is shifted from the emitted wavelength with a difference corresponding to the energetic loss associated with the change Of level of vibration. The lidar analysis of a Raman-vibration scattered signal is similar to that of the Rayleigh signat except that the backscattered and emitted wavelengths are different. The Raman-vibration scattering is roughly 1000 times weaker than the Rayleigh scattering but is weakly sensitive to the aerosols, making its usc possible at lower altitudes (typically between 15 and 35 km).

Sodium layer scattering:

**** Na Lidar description ****

The instruments:

Measurements from three Rayleigh lidars and one Na lidar were used to perform this climatology at mid-latitudes and from one Rayleigh Mar at Iow-latitudes

At mid-latitudes, the CNRS-Service d'Aéronomie Rayleigh lidars of Observatoire-de-Haute-Provence, France (44°N, 6°E, hereafter OHP) and Centre d'Essais des Landes, France (44°N, 1°W, hereafter CEL) have obtained measurements between 30 and 90 km from 1978 to now and from 1986 to 1994 respectively. The NASA-Jet propulsion Laboratory Ozone lidar (Rayleigh) located at Table Mountain Facility, California (34.4°N, 117.7°W, hereafter TMF) has obtained temperature measurements between 30 and 80 km since 1988. The Na lidar of the State University of Colorado at Fort-Collins (hereafter CSU) obtained mesospheric temperature measurements of the Na layer between 80 and 105 km since 1993.

At lower latitudes, the NASA-Jet Propulsion Laboratory Ozone lidar (Rayleigh and Raman-vibration) located at Marina Loa Observatory, Hawaii (19.5°N, 155.6° W, hereafter MLO) has obtained temperature measurements between 15 and 90 km since 1993. Table 1 shows the different characteristics of each instrument.

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Instrument	OHP	CEL	TMF	Csu	MLo
Longitude	6.0° E	1.0” w	117.7° W	105.0” w	155,6° W
Latitude	44.0° N	44.0° N	34.4° N	40.6° N	19.S” N
Altitude (m)	685 .	. ???	2300	???	3400
Instrumental vertical resolution	75 m	300 m	300 m	???	300 m
Altitude range, Rayleigh channel	25 – 95 km	25 – 95 km	25 – 85 km	75 – 110 km	30- 90 km
Altitude Range, Raman channel	.		-	.	15 – 35 km
Estimated error at bottom	< 1 K	< 1 K	< 1 K	~ 15 K	< 0.5 K
Estimated error at mid-range	< 1 K	< 1 K	< 1 K	< (),5 K	< 1 K
Estimated total error at top	-20K	~ 20 K	-20K	~ 15 K	~ 20 K
First year of operation	197s	1986	1988	1992	1993
First year used	1984	1986	1990	1992	1993
Last year used	1995	1994	1997	1996	1997
Emitted wavelength (nm)	532	532	353	???	353
Received wavelength (nm)	532	532	353	999	353/385
Laser energy (mJ/pulse)	400	200	500	???	500
Laser frequency (pulse/s)	50	30	150	???	2.00
Telescope area (m^2)	‘ 0.78/ 0.03	1.44	0.64	???	0.78
Field of view (mad)	0.25/0,55	0.2	2.0	???	1.0

Table 1: Characteristic of the lidar instruments used for this study.

3. Database and data processing

As noted in Table 1, for some instruments with a sufficiently long period of measurements, the oldest years were not used for this study. This applies to OHP (starting measurements in 1978 but using 1984 as the first year) and TMF (starting in 1988 but using 1990 as the first year). There are two main reasons for not using the entire database, 1) For OHP, there were only a limited number of measurements during the years 1978-1983, so that omitting these years does not lose much information. Also, it is interesting to compare the current climatology (19S4 - 1995) with the previous performed by [Hauchecorne et at., 1991] over 1978-1989. 2) For both OHP and TMF, the results obtained during the first months or years of measurements and certainly before processing to an “operational routine mode” may have been affected by some instrumental problems. This is not the case for MLO since the lidar group in charge with this instrument is the same as for the TMF instrument (NASA-JPL). **** what about CSU **‘’.

For OHP and CEL profiles are obtained during the entire night if the weather conditions are good (no cloud, and weak wind), This gives an average of 5-6 hours integration of nighttime measurements, about 4-5 days a week (150-200 profiles per year). For TMF, and MLO, most of the “routine measurement s“ consist in a 2-hours or more integration experiment, usually at the beginning of the night, 4-5 nights a week, insuring a good survey of stratospheric ozone and temperature, as required by the NDSC program. **** what about CSU **•*. Each individual temperature profile is then interpolated every one kilometer, making the data analysis and the comparisons between instruments easier. Table 2 illustrates for each instrument the different characteristics of tire data sets used for this study (individual profiles).

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Data set		OHP	CEL	TMF	CSU	MLO	RUN
Vertical resolution		1 km	1 km	1 km	1 km	1 km	1 km
Altitude Range (km)		30-85	30-85	32-75	80-108	15 - 85	30-75
Estimated error at bottom		< 0.5 K	< 0.5 K	< 0.5 K	< 4 K	< 0.5 K	< 1 K
Estimated error at mid-range		< 1 K	< 1 K	< 1 K	< 0.5 K	< 1 K	< 2 K
Estimated statistical error at lop		-IOK	~ 10 K	~ 10 K	< 4 K	-10 K	-1OK
First year used		1984	1986	1990	1992	1993	1994
Last year used		1995	1994	1997	1996	1997	1995
Number of profiles:	Total	1244	670	686	249	411	149
January		153	60	so	16	39	0
February		109	62	39	26	31	0
March		129	78	50	23	44	0
April		79	50	70	17	4$	9
May		65	45	58	11	3$	18
June		81	46	83	16	40	27
July		10s	56	63	28	17	11
August		99	41	46	24	39	8
September		90	70	58	19	28	14
October		82	57	69	24	32	30
November		119	58	58	23	30	31
December		130	47	42	22	25	1

Table 2: Data set used in this climatology (individual profiles).

It can be noted that the top of the profiles was truncated about 5-10 km lower than the initial cut-off attitude indicated in Table 1. This way, the results containing a non negligible part of "a priori" information and/or noise will not be shown. Also, the bottom of the TMF profiles was truncated at 32 km instead of 30 to avoid any volcanic aerosols effect, especially after the eruption of Pinatubo (eruption in June 1991, major effect in spring-summer 1992 j. The total number of profiles obtained per month is highly variable, depending on the instrument. The most complete database was obtained at OHP, then TMF and CEL, then MLO and CSU. '*'* What about CSU **** . At OHP, CEL, TMF and MLO sites, the effect of the Pinatubo eruption (June 1991) was observed below 30 km. However, above 32 km this effect is quasi-negligible compared to the magnitude of the atmospheric features studied here, ••*• Reference Joe She Pinatubo ****.

For all instruments except CSU the estimated statistical error (i.e. in absence of "a priori" information) at the tap of the individual temperature profiles is still high (~ 5-10 K). But tbe long period and/or the large number of measurements for most of the instruments will reduce this error to few kelvins for the composite daily and monthly mean profiles. High confidence levels are expected Up to 75 km of altitude. • "* Whist about CSU ****

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4. Data analysis and results

a. Climatological temperatures

For each instrument, all individual profiles (from 249 to 1244 profiles depending on the instrument, see Table 2) were computed in a unique composite year of data A weighted running average with a 33-days width triangular filtering scheme was applied to each day of the composite year where at least one profile was available. The remaining days with no profile are filled with an interpolated profile using a two-dimensional minimum curvature spline surface method, and plotted together with the real data Though plotted, these interpolated profiles are not retained in the database, thus avoiding any inaccuracies in the different steps of analysis described below. No tidal removal was pet-formed, In effect, the nature of the data sets allows not taking into account such effect. At mid-latitudes, the semidiurnal component is expected to be dominant, with a few kelvins amplitude at 80 km. For OHP, CEL, and CSU the measurements were taken over the entire tight, minimizing the effect of the 12-hours oscillation At TMF, where measurements are performed during 2 hours in routine mode, the top the profiles is 7S km, where the semidiurnal amplitude has decreased significantly. At MLO, the role of the diurnal tide may not be negligible at 85 km, and the effect of tides will be discussed each time one considers it necessary.\

The composite years obtained for OHP, CEL, TMF, CSU, and MLO are presented in Plates 1a to 1e. The color scale and the altitude range (z_{top}-z_{bottom}) are identical for all instruments for convenience. A typical temperature pattern is observed at all sites, Plate 1e (MLO) clearly exhibits a semiannual cycle at the stratopause (maximum of 266 K at 47 km) and an annual cycle in the lower stratosphere with a very cold minimum of 190 K at 17 km, identified as the tropical tropopause. As expected, the amplitude of the seasonal variations remains weak. At the top (80-85 km), where the effect of the mesospheric diurnal tides is the largest, the plotted cold temperatures are closer to early night temperatures than to nightly (or even a 24-hours) mean temperatures. This will affect some of the results described below, and discussed when necessary.

For OHP, CEL and TMF (Plates la to lc), a classic mid-latitudes warm summer and cool winter stratosphere is observed with a maximum of 272 K in May-June and a minimum of 255 K in early November at the stratopause altitude of 47 km. A classic warm winter and cold summer mesosphere is also observed with a maximum of 220 K in December and January, and a minimum of 195-200 K in May-June at 75 km. For OHP, temperature as low as 175 K are observed at 85 km in June-July, in good agreement with previous climatologies and with the measured 175 K by the Na lidar at Fort Collins (Plate lit). The weak negative vertical temperature gradient observed in winter at OHP, CEL and TMF is the consequence of the seasonal average of the so-called mesospheric temperature inversions occurring during the entire winter at OHP and CEL, and more specifically in February at TMF. A more detailed description of this feature is presented in a companion paper [this issue ?], The temperature pattern above CSU is not very different from that described by Yu and She [1995] in their first climatology. The main difference is in spring and fall, where the so-called "double temperature minimum" is no longer a significant part of the climatology, Instead, a continuously cooling layer in spring and warming layer in fall can be observed between 85 and 95 km, The double minimum is now observable in early April only. As for the temperature inversions, this is the result of the seasonal average. The most significant feature observed in Plate Id is the evidence of a 2-states mesopause, as atready reported by Yu and She. The "winter state" is characterized by a minimum of temperature located about 103 km, with 2 absolute minima (185-190 K) in spring and fall. The "summer state" is characterized by a minimum of temperature at 85 km, with an extremely cold summer mesopause (< 180 K). The transition between the summer and winter mesopause is short and takes less than two months (April-May and August-September) The layer 90-100 km separating both states acts here like an upper boundary to the dynamically driven mesosphere. '**" What about The effect of tides ****.

Since the results obtained are almost identical, data from OHP and CEL will be computed and plotted together, as a single mitt-latihldes site (44°N) called hereafter OHP/CEL. Results from OHP arid CEL will be shown separately only if a significant departure was observed, or if there is a need for an inter-compari son.

b. Temperature deviation from annual mean

In order to identify more clearly the seasonal variation of the temperature, the annual mean temperature profile is subtracted to each available daily composite profile. One thus obtains the composite

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daily deviation from the annual mean. Plates 2a to 2c represent this deviation for OHP/CEL, CSU, TMF, and MLO. For convenience, OHP/CEL and CSU are. presented on the same plot (Plate 2a) since they have quasi-separated altitude ranges. The altitude separating the plotted data from both instruments is 85 km. As expected for OHP/CEL, CSU, and TMF (Plates 2a and 2b), m annual cycle is clearly dominant in both stratosphere and mesosphere. At 67-70 km, its phase with the solar flux gets inverted, leading to the classic warm summer stratosphere and cold summer mesosphere and vice-versa irr winter A second phase inversion is clearly observed at CSU (top of Plate 2a) around 95-100 km., marking the transition between the dynamically and chemically driven mesosphere. These plates, in particular Plate 2a also exhibits a warm late winter centered at 35-40 km This is the signature of the stratospheric warmings occurring from January to March at mid- and high-latitudes. This signature is still observable in Plate 2b, but with a weaker magnitude. Later in the discussion, the effect of the stratospheric warmings will be identified again. Another "warm spot" is observed at 65-67 km in November, reaching 11 K for OHP/CEL, and 8 K for TMF. This feature could already be observed in Plates la to c as a "bump" of warm temperatures in November between 60 and 70 km. This feature will also be discussed later.

In contrast with the mid-latitudes sites, MLO (Plate 2c) primarily exhibits a semi-annual cycle between 25 and 80 km of altitude. This is not surprising since MLO is located at 19.5°N and influenced by the equatorial dynamical pattern. However, and because MLO is not so far away from the mid-latitudes, the semi-annual cycle is strongly modulated by the annual cycle. The late winter maxima and early summer minima of the annual and semi-annual cycles are in phase, making the first oscillation of the semi-annual cycle of larger magnitude than the second. In contrast with the mid-latitude annual behavior, the semi - annual cycle is almost a continuously downward propagating oscillation at an approximate vertical speed of 12 km/month, and can be identified as the thermal semi-annual oscillation (SAO). The so-cal led mesopause and stratopause SAOS appear here as a unique SAO propagating downward from the. mesopause to 30 km, with a modulated amplitude pointing out a minimum at 45 km Surprisingly, 3 "cold spot" can be noted in November at 64 km, almost the same altitude as the previously observed "warm spot" at OHP/CEL and TMF.

c. Annual and semiannual cycles

One can separate now each component by applying a multi-parameter sinusoidal fit of the form:

$$T(t,z) = T_0(z) + T_1(z)\cos\left[\frac{2\pi(t-\varphi_1(z))}{365\ \text{days}}\right] + T_2(z)\cos\left[\frac{2\pi(t-\varphi_2(z))}{182.5\ \text{days}}\right]$$

where T_1 and φ_1 (respectively T_2 and φ_2) are the amplitude (K) and phase (days) of the annual (respectivel y semiannual) cycle, and T_c the annual mean temperature (K) at the altitude z. The amplitudes and phases of the annual and send-annual cycles are plotted for all sites in **Figures 1a-b and 2a-b**.

The agreement between OHP, CEL, TMF and CSU is remarkable for both the amplitude and phase of the annua I and se miannual cycles, The amplitude of the annual cycle. for these sites exhibit s several maxima of 7 K, 20 K, and 13 K located respectively at 35, 80 and 105 km and minima located at 62 km for TMF, 65 km for OHP, and CEL, and 99 km for CSU. The minima correspond, as shown in Figure 1b, to the phase inversion between stratosphere and mesosphere (62-65 km), and to the attitude of transition between the dynamically and chemically driven mesosphere (95-100 km) also leading to a phase inversion at thermospheric altitudes (> 100 km). The main difference between TMF and the other mid-latitudes sites is found in the amplitude between 50 and 60 km, where the TMF amplitude is smaller than for OHP and CEL. This can be easily explained since TMF is located at 34.4°N instead of 44°N and the atmosphere does not behave like at typical mid-latitudes. This will be confirmed later in the discussion. Another significant difference is the altitude of the phase inversion, about 4 kilometers lower than OHP and CEL. This can be explained using the results from Plates 2a-c. in these plates, the most significant fraction of the mid-latitudes annual cycle is L-en during the first six months. During these first six months, the amplitude of the TMF warm cycle has its minimum in early April at 61 km, while for OHP and CEL it has its minimum at 64-65 km. In term of phase, between 55 and 70 km, the TMF warm cycle propagates downward one month earlier than that of OHP and CEL, which correspond to a 4 km difference shown in **Figures 1a-b**. The shift in phase observed at TMF is due to the influence of the early first cycle of the low-latitudes semi-annual oscillation observed at MLO in Plate 2c and Figures 2a-b. For all mid-latitudes sites, the semiannual component is weaker than the annual component, except at the altitudes of annual phase inversion, where it reaches a maximum of 5-7 K at 60-64 km for TMF, OHP, and CEL, and more than 15 K

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at 105 km for CSU. The maximum at 60-64 km is clue to the "warm spot" occurring in November at almost the same altitude as that of the node in the annual amplitude (3 K) occurring in early April. This is confirmed in Figure 2b, with the good agreement between the early November phases at 60-64 km calculated for OHP, CEL, and TMF. The maximum at 104+ /-2 km points out the interplay between the dynamically and chemically driven mesosphere. In June, the dynamically driven mesosphere has its minimum of temperature while the chemically driven mesosphere has its maximum, leading to moderately cold temperatures. In winter, the dynamically driven mesosphere seems to extend far high, also leading to moderately cold temperatures. in spring and fall this dynamical heating is not as efficient as in winter, leading to colder temperatures than irr winter and June. The resulting seasonal variation of the temperature at 104+/-2 km is a semiannual cycle, with maxima in winter and summer, and minima in spring and fall.

d. 2-to 30-days temperature variability

Once one looked at the climatological average, it can be interesting to look at the variability at shorter time states Since most of the initial profiles are integrated over several hours or even over a night, most of the variability owed to gravity wave has been removed, But if one calculates for each daily composite profile the standard deviation from a 33-days averaged profile, one obtains an indicator of the wave activity of all atmospheric waves with periods between 2 and 33 days. These include most of inertio-gravity waves and planetary waves, Of course, the statistical error associated with the lidar measurements should be small enough compared to the variance associated with the waves if we want to extract a significant physical signature. This is not the case in the upper part of the profiles. For this reason, a simple filter, function of altitude and constant in time, was applied to the data. The growth rate of the filter coefficients is related to the atmospheric scale height, since the statistical error is a function of the photon counts, i.e. the atmospheric density, The filter was computed with the assumption of a 10 K statistical error at 93 km of altitude and a 7 km atmospheric scale height. Though not optimized, the filter will remove most of the variance due to instrumental noise in the upper part of the profiles. "l'he filtered standard deviations from the 33 days average are plotted in Plates 3a to 3c for OHP/CEL, CSU, TMF, and MLO. For CSU, the data are not filtered at the bottom (at 85 km, the instrumental error is small enough), and the 10 K assumption is taken at 112 km instead of 93 km By comparing all 3 plates, it is clear that the variability at 2- to 3 3-days has its maximum at mid-latitudes, and decreases significantly as we move towards the tropical latitudes As expected, and previously shown by Hauchecorne et al. [199 l.], the maximum of wave activity at mid-latitudes appears in winter. In the stratosphere, a winter maximum of 10-12 K occurs between 35 and 45 km at OHP/CEL (Plate 3a), twice smaller srt TMF (_Plate 3b). This maximum is principally associated with the stratospheric warmings, and certainly associated with all other inertio-gravity and planetary wave activity. During a stratospheric warming, the winter polar vortex (zonal wave number 1) is broken, leading to weaker westerly winds or even an inversion of the zonal mean zonal winds from westerlies to easterlies. an associated enhancement of the stratospheric temperatures, together with the enhancement of the zonal wave number 2 component When the warming is "major", the mean zonal ruean wind switches to easterlies and the temperature is up to 20 K warmer in few days. After the observed maximum of 10 K around 40 km, and a minimum of 8 K at 55 km, a second winter maximum of 12 K is observed in the mesosphere at OHP/CEL (twice smaller at TMF) between 70 km and 95 km. Then a second minimum occurs around 100 km, The mesospheric maximum is associated with the mesospheric temperature inversions, whose amplitude can frequently reach 40 K [see companion paper], The mesospheric temperature inversions occurring between 65 and 7S km are supposed to be a consequence of the gravity wave breaking [ref]. But due to the basic filter applied here to remove the instrumental variability it is not clear where the mesospheric maximum actually occurs, and what is its actual magnitude. The most important result is that OHP and CSU are in very good agreement again (Plate 3a), and that a maximum of 2- to 33-days variability is observed around 75 km, associated with the mesospheric temperature inversions. In summer, the standard deviation is very low even al mid-latitudes, confirming the weak wave activity during this season at these latitudes. Two secondary maxima are nevertheless observed in early May and early September around 80 km at OHP, while late March and late September appear to be the quietest periods of the year, At MLO (Plate 3c), the extratropical planetary waves are two far away for accounting for the temperature variability, except in the upper stratosphere in December. Larger activity is also observed in the lower stratosphere, showing the high variability of the tropical tropopause. In the

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mesosphere, two maxima arc observed, following a remarkable symmetrical pattern with six months interval.

First reaching 8 K before the equinoxes, they then reach 10 K in early May and November at 83 km. Since tidal amplitudes are not negligible at that height, **and since this lidar located at MLO takes routine measurements with a 2-hours integration time, the maximum** of variability **observed at these altitudes may be related to the tides. More details will be give.o later. No further explanation can presently be given concerning these maxima**

e. Seasonal evolution of the temperature

In order 10 identify clearly the seasonal variation of temperature, one then calculated the time evolution of the temperature, i.e. the time derivative:

$$T'(t, z) = \frac{\delta T}{\delta t} = \frac{T(t+1, z) - T(t-1, z)}{d(t+1, z) - d(t-1, z)}$$

where $d(t)$ and $d(t+1)$ are two consecutive days of measurement (not necessarily two consecutive days). The results arc presented in Plates 4a to 4c with a 10-days time resolution. As for the previous plates, CSU and OHP/CEL arc plotted together, with the OHP/CEL data below 85 km and the CSU data above. Once again, the agreement between OHP/CEL and CSU is remarkable. in the mesospheric and stratospheric mid-latitudes **(Plates 4a and 4b), the summer evolution is quite smooth with a maximum** cooling rate of 4 K/month below 75 km, while the winter evolution is mnch more chaotic as well as during the entire year above 75 km. A non-negligible part of noise may account for this larger variability at that height. However, it is clear that the summer upper mesosphere cools down in two steps. The first step is in February around 85 km, with a maximum cooling rate of 12 K/month, and the second step in late April around 75 km and above. All mid-latitudes instruments (i.e. OHP, CEL, CSU and TMF) agree in this part Then, a first strong heating period takes place in late August (>14 K./month as shown in Plate 4a). This mesospheric warming propagates downward, with a maximum of 10 K/month at 65 km in mid-October. Immediately after this warming period, a short quiet period follows, extending from September around 85 km to late October at 70 km. Then a second strong warming period occurs, with a maximum of 10 K/month at 90 km in October propagating downward with a maximum of 6 K/month in early November, in the stratosphere the winter Cooling occurs in a regular manner (-4 to -8 K/month) in the entire 30-55 km layer. Then, from kite November to late December, the temperature behavior in the mesosphere is driven by the occurrence of the mesospheric temperature inversions. A huge cooling (up to -14 K/month) is observed around 65 km and a moderate warming (+7 K/month) is observed at 75 km, This is in good agreement with some modeling performed by **Leblanc and Hauchecorne** [1997]. In their model, the temperature inversions are the result of mesoscale meridional and vertical circulation cells due to the breaking gravity wave. Ascending motions adiabatically cools the lower part whiJe descending motions **adiabatically** heats the upper part, haling to a large departure from the radiatively determined temperatures. More details are given in [**Leblanc and Hauchecorne, 1997**] and [Leblanc c-t al., this issue], For MLO (Plate 4c), the semiannual oscillation is characterized by weak warming rates (ma.. of 4 K/month at 38 and 45 km in January and August respectively) and cooling rates (around 2 K/month) in the entire middle atmosphere except the upper mesosphere. Above 75 km, stronger values (up to 15 K/month) randomly distributed in time arc observed Once again, a possible explanation is the effect of the mesospheric tides. At these altitudes, the amplitude of the diurnal and semidiurnal tides can reach 5-10 K, However, the different times of measurements do not vary critically (typically, all measurements are obtained within the first 5 hours of the night). Some other effects related to the. statistics and/or the noise have to be taken into account. A longer database may lead to significant insights in the future. For TMF (Plate 4b), an expected intermediary scheme between OHP/CEL and MLO is observed The mid-latitudes annual cycle is dominant, but with some modulation due to the influence of the lower latitudes, For example, the early winter cooling of the stratosphere occurs at the same time as for OHP/CEL (late October), and the summer cooling in the mesosphere behaves like at OHP/CEL. The first strong winter mesospheric warming observed on Plate 4a is also observed for TMF but with weaker amplitude (+8 K/month at 67 km). Then the winter mesosphere behaves quite differently. The strong cooling period between 55 and 65 km occurring from November to December at OHP/CEL, now occurs in late December-early January around 55 km. In addition, the strong warming period observed at OHP at 75 km is no longer observed in December, but in February and at 70 km. The lower latitudes

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seem to affect significantly the temperature behavior at TMF during this period The 4 K/month cooling rate in mid-October at 60 km observed at MLO is in opposite phase with the 10 K/month warming rate observed at 65 km at OHP. The consequence is a moderate warming rate of 4 K/month at TMF. Also, a 6 K/month warming rate observed at MLO at 65 km in early December is in opposite phase with the large 14 K/month cooling rate observed at OHP, resulting in a moderate 6 K/month cooling rate at TMF.

f. Difference with CIRA-86

The composite daily mean profiles were then averaged to obtain the climatological monthly mean temperatures. These temperatures were subtracted to the monthly mean CIRA-86 temperatures. The results are plotted in Plates 5a (OHP and CSU), 5b (TMF) and 5c (MLO). The observed departures from the model have typically 3 origins

The first one is the usually small magnitude of the CIRA temperature variability, compared to the observed temperatures. In our case, this applies at mid-latitudes in the stratosphere, and in the mesosphere above TMF. This is partly due to a large smoothing when computing the CIRA temperatures, together with residual noise and/or variability when computing the observed temperatures. The associated errors remain small, in the order of 1-2 K, and cannot be easily identified.

The second source of departure is related to a systematic bias in the CIRA temperatures, essentially due to the poor or irregular horizontal and vertical resolution of the model. Once again, this error remains small in the middle atmosphere but is not negligible since it can affect an entire layer or season. For OHP and CEL (Plate 5a), the observed temperatures are systematically 2-4 K colder than the CIRA between 30 and 40 km. especially in summer, and 2-6 K colder between 70 and 80 km, while no systematic error is observed at stratopause altitudes. For TMF, no significant departure of this type is observed For MLO, the entire region between 15 and 55 km is colder than the CIRA (up to 4 K in the upper stratosphere). At mesopause altitudes this error is large, as pointed out by the difference CSU-CIRA. A very large positive departure (more than 16 K) is observed in the entire mesopause region (90-95 km). This important point will be discussed later, when comparing CSU and OHP/CEL. Above 100 km, the high temperature variability owed to thermospheric processes leads to a large negative departure of 16 K in summer. The vertical gradient of temperature departure C. SU-CIRA is extremely large in summer, extending from +17 K to –17 Kin 15 km, and suggesting a very poor accuracy of the CIRA at that height.

The third source of error is related to transient processes, like sudden seasonal transitions from summer to winter or stratospheric warmings. The CIRA Temperatures, with a 1-month time resolution can not accurately take into account such processes with time scales shorter than 2-3 months. The errors associated are generally large. For OHP and CEL observed temperatures are up to 10 K colder in December and January, This can be explained by the out-of-phase between the late January-February occurrence of stratospheric warmings at OHP/CEL, and its equivalent occurring earlier for CIRA (December-January). Consequently, the. CIRA is too warm in December and January. In the lower mesosphere, OHP/CEL and TMF temperatures are warmer than the CIRA. A maximum departure of 10 K around 70 km is observed in February at TMF, 4 K at 60 km in Apt-it-May for all mid-latitudes sites, and 4 K (respectively 8 K) at 60-70 km in November above OHP/CEL (respectively TMF). In the middle mesosphere, OHP/CEL temperatures are colder than CIRA, with a maximum departure of 10 K in November at 75-SO km All these departures are due to the difference of behavior in the seasonal transitions The positive maximum in February is due to the second winter warming, where the occurrence of the mesospheric temperature inversions has its maximum above TMF. The positive maxima at 60 km in April and 60-70 km in late fall are respectively related to the late winter warming (February-March) and to the first winter warming (October), The negative maximum at 75-80 km is related to the stationary period trapped in October between the first and second winter warmings.

For MLO (Plate Se), the temperature departures are smaller than at mid-latitudes This is not surprising since the variability is itself smaller at low-latitudes. Consequently, the systematic errors, the errors owed to the annual and semi-annual amplitudes, and the errors owed to the seasonal transitions are all minimized. In the entire middle atmosphere except two times of the year between 60 and 70 km, the CIRA is warmer. In the stratosphere, this systematic departure is about 2. At SO km a maximum of 10 K negative departure can be observed For the same reasons explained in the previous subsection, this large departure is partly due to the mesospheric tides. Moreover, a very typical pattern is observed at the beginning of the year: A negative departure is propagating downward from 80 km, associated with a positive departure around 65 km, and a negative departure again between 50 and 55 km. The similarity in

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the downward propagation for these three different layers suggests a possible outward sign of a wavelike structure. In fact, the associated vertical wavelength is close to that of the diurnal tide (2S km for the first mode), suggesting that the temperatures measured by lidar at MLO are representative of early night temperatures. It is not unlikely that most of the observed departure in the middle and upper mesosphere is related to tidal effects. This will be investigated more in details during the next months A longer database at MLO is anyway necessary to provide a more detailed explanation.

g. Inter-comparison OHP/CEL-TMF and OHP/CEL-CSU

The monthly mean temperatures at OHP, CEL, CSU and TMF were then compared. Between 70 and 80 km, the difference OHP-CEL does not exceed 6 K. Below 70 km, this difference never exceeds 4 K, with a typical values comprised between –2 and +2 K, For this reason, we show only the difference between OHP+CEL together and TMF (Plate 6a). Again, the largest differences are observed in winter. The positive difference observed in November at 60 km cm-responds to the difference of the magnitude of the first winter warming period already pointed out The strong negative difference from December at 60-65 krn to February-March at 70 km is the consequence of the delay in the occurrence of the mesospheric temperature inversions, as described previously. The positive differences observed in the stratosphere in January is a consequence of the weak warming period observed at TMF in February associated with the January cooling period at OHP and CEL. No explanation of this difference can be given at this date. In summer, the positive difference at 50 km simply corresponds to the latitudinal variation of the warm phase of the annual cycle, occurring 2 weeks later at TMF and with a weaker amplitude. The difference between the OHP+CEL temperatures and the CSU temperatures are given in Plate 6b. The overlapped altitudes are initially 75-90 km, but the significant results actually appear between 83 and 87 km only In fact, the lower part of the CSU profiles have a systematic positive error due to the Na lidar analysis method. This is clearly observed in Plate 6h. Above 87 km, the OHP and CEL temperature profiles contain a non-negligible part of CIRA climatology duc to the a priori initialization at the top. The positive difference observed above 85 km in Plate 6b is therefore not surprising. In effect, since the CIRA above CSU seems much too cold at 90-95 km (see Plate 5a) and does not differ significantly from that above south of France, the temperature initialization using CIRA might lead to too cold temperatures at the top of the OHP and CEL profiles. For this reason, temperature initialization using Na lidar climatological data is currently under investigation by the CNRS/SA and JPL lidar groups

h Inter-annual variability rrnd Observation of the QBO

Figures: OHP, CSU, TMF, MLO ??

5 Discussion and Conclusion

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