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NOCTILUCENT CLOUDS AS POSSIBLE INDICATORS OF GLOBAL CHANGE IN THE MESOSPHERE

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ABSTRACT

Noctilucent clouds (NLC) are ice clouds near the high-latitude mesopause region, occurring in summer. These clouds have been implicated as possible harbingers of permanent changes in the upper atmosphere. Their year-to-year variations have been characterized by a semi-quantitative index, the number of nights per season in which they were reported. In this paper we compare early studies of NLC year-to-year variability with data from the modern era, including observations from Europe, the USSR and North America. This review focuses on the possible influence on NLC of water vapor variability. We compare the noctilucent cloud time series, which indicate a strong upward trend in the 1964-1986 period, with changes expected of atmospheric water vapor at the mean height of the clouds (83 km). At this height, both methane-induced changes and 11-year solar-UV induced changes are expected to be the main forcings. Using the data available for surface methane and for solar Lyman-alpha fluxes, we estimate the water vapor changes due to methane oxidation, and to Lyman-α induced photodissociation of water vapor. For the periodic (10-year) component, the NLC time series was found to significantly correlate with Lyman-α flux data, for nearly all available multi-decadal NLC data sets. As first shown by Gadsden for the European data, the correlations are highest when the time lag of NLC following solar cycle minimum is two to three years. This result places into considerable doubt the hypothesis of direct solar Lyman-α control of NLC. Volcanism appears to have had a negligible influence, with the possible exception of the 1883 Krakatoa eruption. © 2001 COSPAR. Published by Elsevier Science Ltd. All rights reserved.

INTRODUCTION

Noctilucent clouds (NLC) exist only at latitudes northward of 50°, and ordinarily occur only during the summer months. They have their southern counterparts at similar latitudes and times relative to summer solstice. They are almost certainly small water-ice particles, created in the extremely cold (120-140K) mesopause region near 88 km. Their most observable manifestation as thin (1 to 3 km) layers near 83 km is thought to be due to sedimentation downward from their height of origin, and growth by acquisition of water vapor (henceforth H_2O) in the denser regions. Their optical visibility is greatest at the bottom of the saturated region, where the particle sizes maximize. For a good introduction, see Gadsden and Schröder (1989). Current interest in this subject stems from the possibility that NLC are the markers of global change in the upper atmosphere (Thomas et al., 1989; Thomas, 1996a). Our aim in this paper is to study the time series of NLC observations, with the hope of understanding the physical forcing mechanisms. High H_2O concentrations and low temperature favor the existence of more numerous and larger particles, hence brighter and more frequent clouds (Thomas, 1995). By NLC *climatology*, we mean the year-to-year variability of the number of NLC occurrences summed over an NLC 'season'. This was the subject of several previous investigations (Fogle 1965; Vasil'ev, 1973, Gadsden, 1998; Schröder, 1999). The observational record extends back to their discovery in 1885. Fogle and Haurwitz (1973) compiled a large number of early published observations. They screened out the obvious false sightings, and plotted the number of reported nights per season of NLC from 1885 to 1969. They suggested that the sporadic nature of NLC occurrence was a result of major 'Plinian'-type volcanic eruptions, because of their presumed enhancement of the H_2O content of the upper atmosphere.

Thomas et al. (1989) suggested that the discovery of NLC in 1885 was the actual debut of the phenomenon, being due to a combination of a slowly-increasing H_2O trend, and a temporary enhancement of H_2O and/or sublimation nuclei due to the 1883 Krakatoa eruption. Gadsden (1990; 1997; 1998) has analyzed the reports of annual ground sightings for Northwestern Europe and the USSR. The European data contained both a 10 year cyclic trend, and a longer-term trend, the latter amounting to a doubling of NLC numbers from 1964 to 1985. Gadsden (1990) ascribed this increase to a decrease of mesospause temperature by about 7K. Temperature fluctuations are undoubtedly important for affecting NLC visibility on any given day, and for driving the seasonal cycle. However there is no clear body of evidence, either experimental or theoretical, that supports a significant long-term cooling at the summertime mesopause (Thomas, 2000; Olivero and Thomas, 2001). More data are clearly needed. In this paper we consider the evidence that water vapor variability could be responsible for both the periodic and long-term trends in NLC occurrence.

We revisit the ground-based NLC data base, including all available data for which there is year-to-year continuity and homogeneity of reporting. These data fall into two general categories: the early era for which the cloud sightings were simply culled from the literature. For the modern era when observing networks were set up, a more reliable NLC climatology can be constructed. We consider all the major sources/sinks of middle atmospheric H_2O, and their long-term variability: (1) volcanism; (2) transport of tropospheric H_2O through the tropical tropopause; (3) methane conversion; and (4) solar ultraviolet (UV). A simple model is constructed for the long-term averaged H_2O concentration, including factors (2), (3) and (4). The H_2O concentration at 83 km is projected backward to the 19th century, using historical records of sunspot number and ground-based methane. Comparisons of the H_2O variations with the NLC time series suggest that methane increase and solar forcing have been the strongest factors in NLC variability. In the last section, we summarize and conclude with suggestions for future research.

EARLY ERA (1885-1957)

One of the earliest reliable NLC climatologies was constructed by Fogle (1965). His compilation is shown in Figure 1. Fogle and Haurwitz (1973), describing the same data set, defined six periods of enhanced activity up to 1969: (1) 1885-1890; (2) 1908; (3) 1925-1929; (4) 1932-1938; (5) 1951-1959; and (6) 1963-1968. They ruled out solar activity as a forcing agent, since these periods occurred at various parts of the 11-year sunspot cycle. This conclusion was supported by Schröder (1966), using data from Germany for the period 1885-1964. Fogle and Haurwitz found that most of the active periods were preceded by either an explosive volcanic eruption (generally in equatorial regions) or a high-yield nuclear weapons test in the atmosphere. They reasoned that such events would have injected large amounts of moisture-laden air into the stratosphere, and subsequently be transported to the mesosphere.

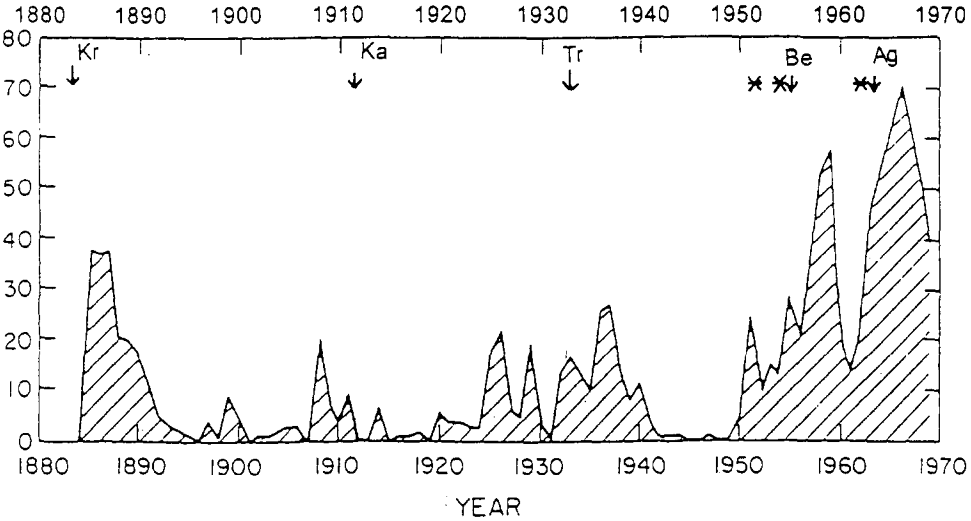

Fig. 1. Yearly variation of reported NLC activity (from Fogle, 1965). The years of major volcanic eruptions and weapons tests are shown as arrows (↓) and asterisks (*), respectively. Kr, Ka, Tr, Be, and Ag denote the volcanoes Krakatoa, Katmai, Trident, Bezymjannya, and Agung, respectively.

Vasil'ev (1973) reviewed the catalog of NLC nights observed in the USSR, confining his attention to observations from the western part of the country. He identified both 11-year and 3.65 year periodicities in the 1920-1941 record. His tabulation is plotted in Figure 2, along with that of Fogle, and other more modern data, to be discussed in the next section.

Some of the year-to year fluctuations shown in this early data are probably not real. Poor weather conditions, changes in the number of observers, etc. place into doubt the accuracy of these historical time series. Vasli'ev (1973) criticized the Fogle tabulation as being inhomogeneous, containing observations from differing longitudes in different time periods (this is certainly true of the late 1950s when there was addition of many new observers in the eastern USSR during the IGY, and IQSY).

THE MODERN ERA (1957-PRESENT)

In the modern era, two different lines of evidence arose. The first was the emergence of a high-quality ground-based index of NLC activity (Gadsden, 1998, and others). The second was the availability of space-age data which led to a detailed understanding of the physical environment of mesospheric clouds. The former work has caused a renewed interest in global change in the mesosphere, and the latter has placed the studies of NLC on a firm physical basis. Although in principle, global trends of mesospheric clouds are best determined from space observations (as Polar Mesospheric Clouds), there is not yet a sufficiently long data base to assess long-term trends (see Thomas, 1995).

It was appreciated by mid-century that understanding such a global phenomenon required a network of trained observers, reporting to a dedicated central organization., By the 1950s, networks had been established in Scotland, the USSR, and later in North America. A massive observing effort was undertaken in the USSR during the IGY beginning in 1957, and the IQSY in 1961 (Bronshten and Grishin, 1970). Two groups are currently active, in Northwestern Europe (Simmons and McIntosh, 1983) and in North America (Zalcik, 1998).

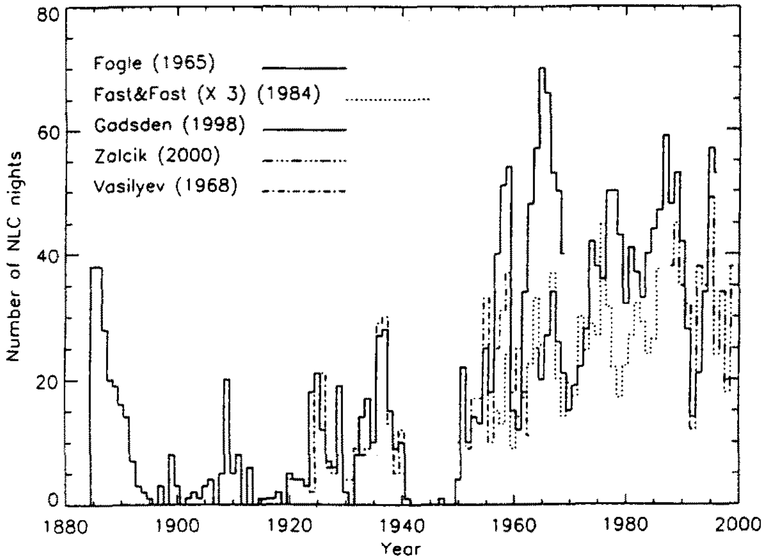

Fig. 2. Yearly variation of reported NLC activity: Solid line: Fogle (1965); dotted line: Fast and Fast (1989); dashed line: Gadsden, Europe (1998); dashed-dotted line; Zalcik (2000), and dashed line, Vasil'ev (1973). The Fast and Fast data have been arbitrarily multiplied by 3 to more closely agree with other data.

Time series of NLC observations in the USSR have also been tabulated by Fast and Fast (1989), and are shown in Figs. 2 and 3. In addition, North American observations reported by the Canadian-Alaskan (CAN-AM) network (Zalcik, 2000) are also shown. There are undoubtedly some observations included in several data sets (for example between the various USSR data sets). In Figure 3, we have plotted the modern data, for which there are multiple data sets, but omitting the Fogle data because of their inhomogeneous character. Shown in Figure 3 are the times of solar maximum and minimum, and of the three major volcanic eruptions during this time. Although the data differ in detail, they are somewhat correlated, particularly in containing a clear decadal-length oscillation. As Gadsden (1998) has pointed out, it is tempting to ascribe this periodicity to the solar cycle. However, Gadsden found that the period lay between 10.3 and 10.5 years, significantly different from the 11-year solar period. The question of solar forcing will be discussed in the next section. The European and USSR data both display a long-term trend, as reported by Gadsden (1990; 1997; 1998). The long-term trend has apparently disappeared over the past 15 years, being absent in both the European and North American data sets. This may be explained (Gadsden, 1998) by the fact that the number of NLC nights has been approaching the length of the season ('saturation'). We turn to a possible explanation of the periodic and long term variability of NLC, in terms of mesospheric water vapor variability.

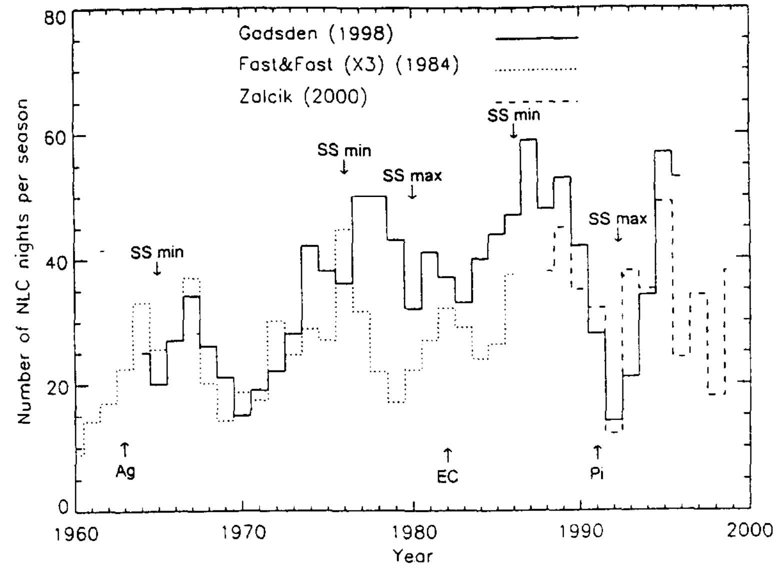

Fig. 3. NLC activity index for four modern data sets (see Fig. 2), omitting the Fogle data shown in Figs. 1 and 2. The times of solar cycle maxima and minima are shown, as well as the dates of major volcanic eruptions (Ag=Mt Agung, EC=El Chichon, and Pi=Mt. Pinatubo).

SOURCES OF WATER VAPOR AND THEIR LONG-TERM VARIABILITY

Volcanism: In this section we consider various sources of H_2O and their variability, (1) through (4) mentioned above, beginning with volcanism. As seen in Figure 3 there is no obvious signature in the NLC data from either the Mt. Agung or El Chichon eruptions. However, a case could be made that the very low occurrence rate in 1992 and 1993 was a result of the 1991 eruption. We believe that this minimum is caused by the solar activity maximum in 1991. Furthermore there is no evidence of volcanic influences in the 21-year time series of upper stratospheric H_2O (Olivero and Thomas, 2000). It is curious that lidar soundings at 40N latitude show a warming episode of the mesopause region from 1992 to 1996 (Krueger et al., 1999). However, this warming peaked in 1994, *three years* following the 1991 Pinatubo eruption. It is difficult to imagine a physical warming mechanism that would act more quickly at the high latitude mesopause, than in a region closer in latitude to the site of the eruption. It may be possible to reconcile these apparently disparate behaviors, using satellite data of temperature from the Upper Atmosphere Research Satellite (UARS). How does the absence of a clear and unambiguous volcanic signature in recent NLC activity affect our hypothesis (Thomas et al., 1989) that the abrupt onset of NLC in 1885 was caused by additional H_2O (or condensation nuclei) issuing from the 1883 Krakatoa eruption? It is clear that there are many uncertainties (see Mills et al., 2001 for a further discussion of these points). One possibility discussed in the conclusion section is that Krakatoa may have been unique among all of the eruptions of the last several centuries. It may have had a singular effect on NLC lacking in the other eruptions.

Tropospheric Source: About half of the stratospheric content of H_2O originates in the troposphere, as a result of ascent in the tropical Hadley cell (Hurst et al., 2000; see also references in Zhou et al., 2001). The other half comes from oxidation of methane (CH_4), although conversion is not complete below ~70 km. The methane-caused trend is about 1/2% per year, and cannot explain satellite measurements which indicate trends in the early 1990s as high as 2% per year at 40 km height (Smith et al. 1999). The trends have apparently leveled off, or even become negative in the latter 1990s . It is clear that such changes cannot be ascribed to the monotonically increasing methane source (see below) and must be due to variable injection from the troposphere. This source was apparently variable over a much longer time period. Rosenlof et al.(2001) reported that lower stratospheric H_2O has increased by about 1% per year, for the past 45 years.

Methane Source: Water vapor at the mesopause should have increased by ~50% over the past century because of increased atmospheric methane (CH_4). It is well established that the surface concentration of CH_4 has doubled in the last 100 years (Khalil and Rasmussen, 1994). CH_4 oxidizes in the middle atmosphere (40-70 km), ultimately resulting in H_2O. This source adds to the tropospheric component. The fact that the total hydrogen content is conserved in a vertical column allows us to estimate H_2O changes in the mesosphere (Thomas et al., 1989). This conservation principle obviously breaks down in the NLC region itself, since condensation and sedimentation tend to remove H_2O. However, since the evaporated H_2O is recycled upward by vertical advection, the net amount supplied to the region should respond to long-term changes in total hydrogen. It is also a useful rule that each CH_4 molecule is ultimately converted to (approximately) two H_2O molecules in the lower mesosphere (Hurst et al., 1999). 'Potential water', a measure of the total number of hydrogen atoms in the stratosphere and mesosphere is given by

$$(H_2O)_p = (H_2O)_0 + 2*(CH_4) + (H_2) \qquad (1)$$

where (CH_4) and (H_2) denote the mixing ratios of methane and molecular hydrogen, respectively. $(H_2O)_0$ is the tropospheric component, described above. H_2 is a minor (10%) contributor to $(H_2O)_p$ below about 75 km, but rises in importance into the mesopause region where it may contribute 50% to the total (LeTexier et al., 1992. $(H_2O)_p$ is ~7 to 8 ppmv. The quantity $(H_2O) + 2.* (CH_4)$ has been measured by the HALOE satellite experiment since 1991, and provides an excellent data base for our purposes. In order to estimate (H_2O) in the mesosphere, it is useful to define the ratio, R(z), such that $H_2O(z) = R(z)*(H_2O)_p$. In the stratosphere, R(z) increases with height, as CH_4 becomes converted to water. At mesopause heights, where solar photodissociation of H_2O occurs, its mean value is about R~0.59, and varies with solar UV flux. An important assumption is that there is no long-term variability of the value of R at a given height, apart from the (hopefully) predictable solar cycle modulation. In other words for a given solar flux, *the chemical partitioning does not vary with time*. Methane doubling modeling has verified the constancy of the partitioning in time (Portmann, 1994; see also Brasseur et al., 2000). Since R(z) may be determined from satellite data, or from a model, then given the time history of H_2O and CH_4, the changes in mesospheric H_2O may be estimated at the mean 83-km height of NLC. Olivero and Thomas in a companion paper estimated that, as a result of the observed upward trend of CH_4, H_2O (83km) should have increased during the 20th century, from 2.6 ppmv to its observed value in 1992 (3.6 ppmv, measured by the Microwave Limb Sounder at 60° latitude; Pumphrey, 1999). However, as discussed previously, this rate of increase is about half that shown in a 21-year time series of space measurements of H_2O at the 3mb pressure level, about 40 km (Olivero and Thomas, 2000). A consistent trend was present in lower stratospheric water vapor for a much longer period of time, amounting to ~2 ppmv in 45 years (Rosenlof, 2001). However, we have no information on stratospheric H_2O for longer time spans, and thus we have chosen to use the more conservative rate of increase, determined by methane changes alone. The surface values of methane concentration are well documented over the past century.

Solar cycle effects: As discussed in the last section, NLC occur most frequently during periods of solar minimum activity. However testing an obvious physical mechanism of solar UV heating, and water vapor photodissociation was not possible until an extensive set of solar measurements became available. The Lyman-α (Lα) emission line at 121.6 nm contains the bulk of the ultraviolet energy deposited near the mesopause. The flux from this important part of the solar spectrum has been measured from space for several decades. In the absence of measurements, it can be approximated using a ground-based radio (10.7 cm) flux proxy back to 1947. The Lα flux is now known to vary by ~50% from solar minimum to solar maximum (Woods et al., 2000). As pointed out by Garcia (1989), Lα variability should significantly alter the mesopause H_2O concentration over the 11-year solar cycle, and thus influence NLC occurrence. Calculations show that a change of 50% in mesospheric H_2O could have a tenfold effect on the brightness of ice clouds (Jensen, 1989; Thomas, 1995). Thus we would expect NLC to become both brighter and more numerous during solar cycle minimum. This notion was supported by observations of an apparent solar-cycle dependence of the occurrence rate of bright Polar Mesospheric Clouds (Thomas et al., 1991). However Gadsden (1998) has emphasized that there is no evidence for systematic changes in NLC brightness. Moreover, when the time lag of the 10-year oscillation in the European NLC data was analyzed, using the 10.7 cm radio flux index as a proxy for solar UV, Gadsden (1998) found a *two-year time lag*, following solar minimum. As pointed out by Gadsden, this is not consistent with the comparatively rapid (one-to-two week) lifetime for photodissociation of water vapor, and "throws great doubt on assigning the 10-year cycle in NLC frequency to photodissociation of water vapor at the mesopause". To test the robustness of this result, we subjected the other data sets to a lagged cross-correlation analysis, using the Lα data from Woods et al. (2000). For the various data sets, the time lag with respect to the Lα minimum, and % confidence levels was found to be (1) Gadsden, 2 to 3 years, 99%; (2) Fast and Fast, 0 to 2 years; 99%; (3) Zalcik, 1 to 2 years, 42%, thus not significant; (4) USSR data shown in Gadsden (1990), 3±1 years, 99%; (5) Vasil'ev (1920-1941), 3 years, 95%. For the older data set of Vasil'ev, we used the sunspot number as a Lα proxy (see below). Remarkably, Gadsden's result is verified (within ±1 year) by all the available data sets. We now turn to estimating the mesospheric water vapor mixing ratio over the past century.

Simple Water Vapor Model: We assume that the 83 km H_2O variations are described by a product of two factors: (1) F_1 due to solar variability and (2) F_2 due to a long-term increase from methane oxidation. To estimate F_1 we assume a linear response factor f, defined as the ratio of the change of H_2O to the corresponding change of Lα flux so that $\Delta H_2O/H_2O=-f^*\Delta L\alpha/L\alpha$. Here ΔX/X denotes a fractional change in the quantity X. Chandra et al.(1997) analyzed 4 years of UARS HALOE satellite data to show that f~1 for mid- and low latitudes at 80 km, agreeing well with their model predictions. However at high latitude, where the solar rays are more slanting, and where the stronger upwelling of H_2O tends to dampen the H_2O response, f is smaller than 1. We will use the result of Jensen (1989) who found that f=0.5. The average value of our H_2O model for the modern era was set equal to the 83-km MLS water vapor amount mentioned above. We further use June and July averages for the Lα flux, taken from the data base of Woods et al. (2000). The factor F_1 is the product of R, the H_2O partition factor, and the potential water $(H_2O)_p$ given by eqn. 1. We allow the methane term, and hence the potential water to vary in time according to the data of Khalil and Rasmussen (1994) (see Figure 3 of Olivero and Thomas, 2000). Thus $(H_2O)= F_1F_2$ where $F_1=(1.-f^*\Delta L\alpha/L\alpha)$, and $F_2=R(H_2O)_p(t)$. We assume a constant value of $(H_2O)_o=2.7$ ppmv from Jones et al. (1986). Further, we include a 7-year time lag to account for the transport time from the ground to the mesopause (Zhu et al., 2000). Setting f=0.5 and R=0.486 we show the results in Figure 4a. In the lower panel of Figure4 we show the scaled NLC activity index from 3 data sets. The correlation with the scaled NLC observations is very good but, as discussed previously, the observed 2-to 3-year time lag forbids a simple interpretation of Lα control of H_2O and NLC.

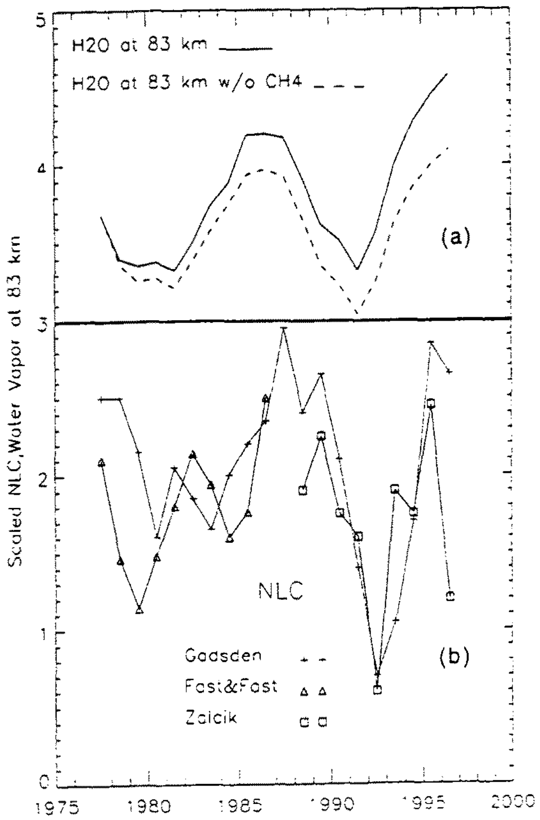

Fig. 4. (a) Estimated mesospheric water vapor, with (F_1 F_2) and without (F_1) the CH_4 increase. (b) Scaled NLC activity index from 3 data sets (shown in Fig. 3).

Since the data extend back to 1885, it is interesting to estimate the time progression of mesospheric H_2O over the entire 115-year time span of NLC observations. We will include both Lα variability and methane increases. For the former, it is necessary to use a ground-based proxy indicator of solar UV. For our purposes, the Zurich sunspot number (available to 1748) is a moderately good proxy for Lα flux. For the 1947-1999 period in which direct Lα measurements are available, we have determined a simple quadratic fit of Lα flux with the sunspot number SS (both averaged over the summertime months). The results are:

$$L\alpha = a_0 + a_1 * SS + a_2 * (SS)^2 \qquad (2)$$

where Lα denotes the solar flux in units of 10^{11} photons/cm^2/sec, a_0= 3.01, a_1=0.0254, and a_2=-7.22x10^{-5}. The standard deviation of the fit is better than ±10%.

The results for the entire time span are shown in Figure 5. Shown as filled circles are the periods of NLC enhancements according to Fogle and Haurwitz (1973), and in addition those of Figure 4b. We will discuss the correlations, working backwards in time. The times of enhanced NLC of the last five solar cycles *coincide with the calculated water vapor maxima due to solar minimum activity*, with due allowance for a few years time lag. The previous cycle occurred when there were few reported observations (1941-46). The first NLC enhancement period for which the correlation breaks down is that of 1925-1929, which coincided with the *maximum* phase of solar cycle 16. The H_2O peak in 1902 should have coincided with an NLC enhancement. Finally, the first recorded NLC episode, that of 1885-1890, coincided nicely with sunspot minimum (H_2O maximum). However the discovery year (1885) itself was not in a solar minimum period.

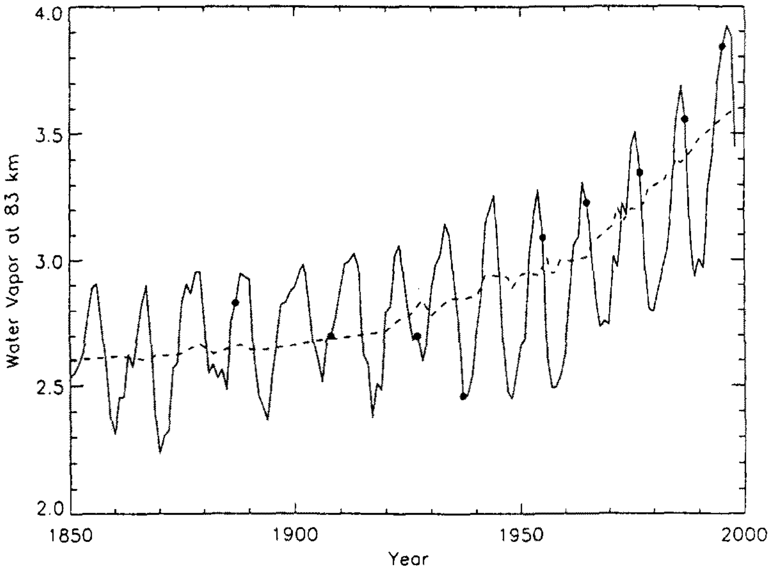

Fig. 5. Estimated mesospheric water vapor, with a methane increase only (dashed curve), and including solar cycle modulation (solid line). The filled circles indicate the dates of NLC enhancements (see Figures 1, 2, and 3). The H_2O amount has been normalized to 3.6 ppmv in 1998.

Several questions emerge. Why were NLC not observed (or at least not reported) prior to 1885? Jesse and Tseraskii both claimed they would have spotted even weak NLC, had they occurred in the 1875-1885 period (Fogle and Haurwitz, 1973); Why didn't they observe an NLC display in 1878? Why weren't NLC reported in 1902 or in 1921? It should be noted that during the First International Polar Year (1882-1883), when there were many scientists watching the polar skies (Schröder, 1999), there were no reported sightings of any phenomena that could be interpreted as an NLC. Perhaps their absence was due to too little water vapor, due to the lower methane amounts, and also the high solar flux (1882 was a year of solar maximum activity).

SUMMARY AND CONCLUSIONS

1. There is a complete lack of pre-1885 reports of phenomena that could later be interpreted as NLC (Thomas et al., 1989; Schröder, 1999). Such an impressive spectacle would have been noted by nineteenth century sky observers, but there are no published records even suggesting a sighting of such a phenomenon. This does not prove, but strongly suggests that NLC actually underwent an abrupt increase in numbers in the "discovery" year, 1885. These first few years of impressive displays were followed by a slow decrease to a

minimum around 1900. There is evidence of an upward trend in numbers of NLC, particularly after 1950, and lasting until the mid 1980s when the activity leveled off at its present value of about 40±20 clouds per season.

2. It is now well established that NLC has a 10-year periodic component, whose period is close in value to the familiar 11-year solar period. However the mechanism of forcing of mesospheric H_2O by solar UV (predominantly Lα) does not explain the ten-year periodicity of NLC, nor more importantly, the two to three-year time lag of NLC following solar cycle minimum (water vapor maximum). The absence of this 10-year component in the early era is not understood, but is probably a result of the inhomogeneity of the early compilations.

3. As also discussed by Olivero and Thomas (2000), even the recent large volcanic eruptions, such as El Chichon and Pinatubo, did not have a significant effect on the H_2O content of the middle atmosphere. Neither was there any noticeable effect on the NLC record. This is undoubtedly due to the fact that the amount of injected H_2O in most eruptions is small compared with that naturally present. However, Krakatoa may have been unique in this regard. This event took place on a small island where breaching of the crater rim by seawater caused heated steam to add to the volcanic explosivity, in addition to causing the injected plume to be rich in H_2O. This contrasts with all other 20th century volcanoes, which were water-poor injections of sulfates and involatile ash particles.

4. Through simple continuity arguments, long-term increases of methane should have caused a gradual increase in mesospheric H_2O. Models suggest an accompanying increase in NLC brightness, implying an increase in the number of NLC occurring over the past century. However, Gadsden (1998) has argued that there is no evidence for significant increases in NLC brightness. Presumably, a more complete model might be capable of explaining increased numbers of clouds in terms of increasing moisture, without increasing their mean brightness. This is a problem area which deserves more attention.

5. Methane-induced trends in H_2O are inadequate to explain the upswing in NLC numbers during the 1964-1984 period. This trend may have been a result of increases in the tropospheric component, for which there is current evidence of variability over sub-decadal time scales. (However, there is no sign in NLC activity of the increased water vapor in the early 1990s .) Possibly the recent absence of an NLC trend is a result of the index reaching a "saturation" level. A problem with this idea is that one would expect that the *minima* to continue upward, since they are in the same range as the earlier values showing a strong trend.

This paper has emphasized the periodic and long-term properties of NLC. It has attempted to explain these properties in terms of a single variable, water vapor, which depends upon the methane content and upon the effects of solar UV variability. However, there are serious problems with the simple hypothesis of solar control by UV heating and/or photodissociation. Since mesospheric H_2O is influenced by vertical advection there is the possibility that changes in the mesospheric circulation are forced from below by mechanisms with long time lags (Gadsden, 1998) Of course, if temperature trends are present, many of these conclusions need to be modified.

Future progress can be expected from comparisons of space-based data taken over various parts of the solar cycle, since various data sets of PMC on multi-year time scales are now becoming available (such as from SAGE-II, SBUV, SNOE, POAM-II and III, and MeteoSat). It is also very important that the NLC networks continue their valuable observations.

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