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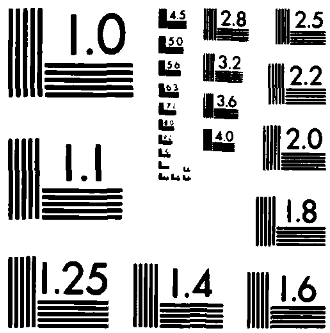

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ABSTRACT

The study of noctilucent clouds (NLC) is one century old, yet the origin and nature of these clouds is still uncertain. It is known that these clouds form in the cold, high latitude summer mesopause region where temperatures can approach 110K. Their association with the very cold air in this region supports the theory that they consist of water ice particles. It has been suggested that NLC are anticorrelated with aurorae since aurorally induced effects at or near the mesopause may lead to processes which retard or altogether inhibit NLC formation. This study will review some general characteristics of NLC, polar mesospheric clouds (PMC) and aurorae and then discuss several ways in which aurorae may interact with these clouds.

The Pennsylvania State University

The Graduate School

Department of Meteorology

On the Possible Anticorrelation of Polar Mesospheric (Noctilucent) Clouds and Aurorae

A Paper in

Meteorology

by

Stephen S. Carr

Submitted in Partial Fulfillment

of the Requirements

for the Degree of

Master of Science

August 1986

We approve the paper of Stephen S. Carr.

Date of Signature

23 June 1986

John J. Olivero, Professor of Meteorology, Thesis Advisor

23 June 1986

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1.0 INTRODUCTION

The upper mesosphere is a region of the atmosphere which is still remote and mysterious to science. Instrumented balloons cannot reach this altitude and in situ rocket sampling is very expensive and frequently yields inadequate results. The lack of data from this altitude region is unfortunate because many interesting physical phenomena occur there. But satellites, such as the Solar Mesosphere Explorer (SME), are improving the database now by allowing scientists to add space-based observations to their already extensive ground-based observations. It has been suggested that the occurrence of noctilucent and polar mesospheric clouds is anticorrelated with auroral activity. By investigating this possibility using satellite and ground-based data, a better understanding of the physical processes which shape the upper atmosphere may be developed.

1.1 Background Information

Scientists classify regions of the atmosphere according to their thermal and electrical structure. Both types of classification will be used in this paper. The mesosphere is a region of the atmosphere bounded at about 50 km by the stratopause and about 85 km by the mesopause; in this region, the temperature generally decreases with height. The summer polar mesopause, the region of interest in this study, is the coldest level in the entire atmosphere. The stratosphere, the region directly beneath the mesosphere, contains most of the ozone which efficiently absorbs UV radiation causing the temperature to increase with height. The thermosphere, the region directly above the mesosphere (> 85 km), is another zone in which temperature increases with height (see Figure 1).

At polar latitudes in the stratosphere, solar UV radiation can be absorbed by ozone 24 hours per day thereby heating this region tremendously. The strong updraft in the stratosphere creates a mean upward motion in the summer polar mesosphere. With air parcels in the mesosphere displaced adiabatically upward, expansion and net cooling occurs, making the summer polar mesopause the coldest level of the atmsophere. This upwelling of air ends abruptly at about 90 km where it is diverted meridionally towards the winter pole creating a direct circulation (Brasseur and Solomon, 1984). Although the winter pole receives no sunlight, its temperature is generally 50K higher than that of the summer pole - a result of the dynamical effects which establish the temperature structure in the middle atmosphere. The temperature generally decreases with latitude in summer at the mesopause and increases with latitude in winter.

When studying atmospheric ionization, it is convenient to classify the atmosphere according to its electrical structure rather than its temperature structure. Very short wavelength solar radiation ionizes neutral particles so that a region of ions, electrons and neutrals exists in the upper atmosphere. This is called the ionosphere and it is divided into three regions: the D-region from 60-90 km, the E-region from 90-160 km and the F-region above 160 km (Craig, 1965). Thus, the D-region basically corresponds to the mesosphere.

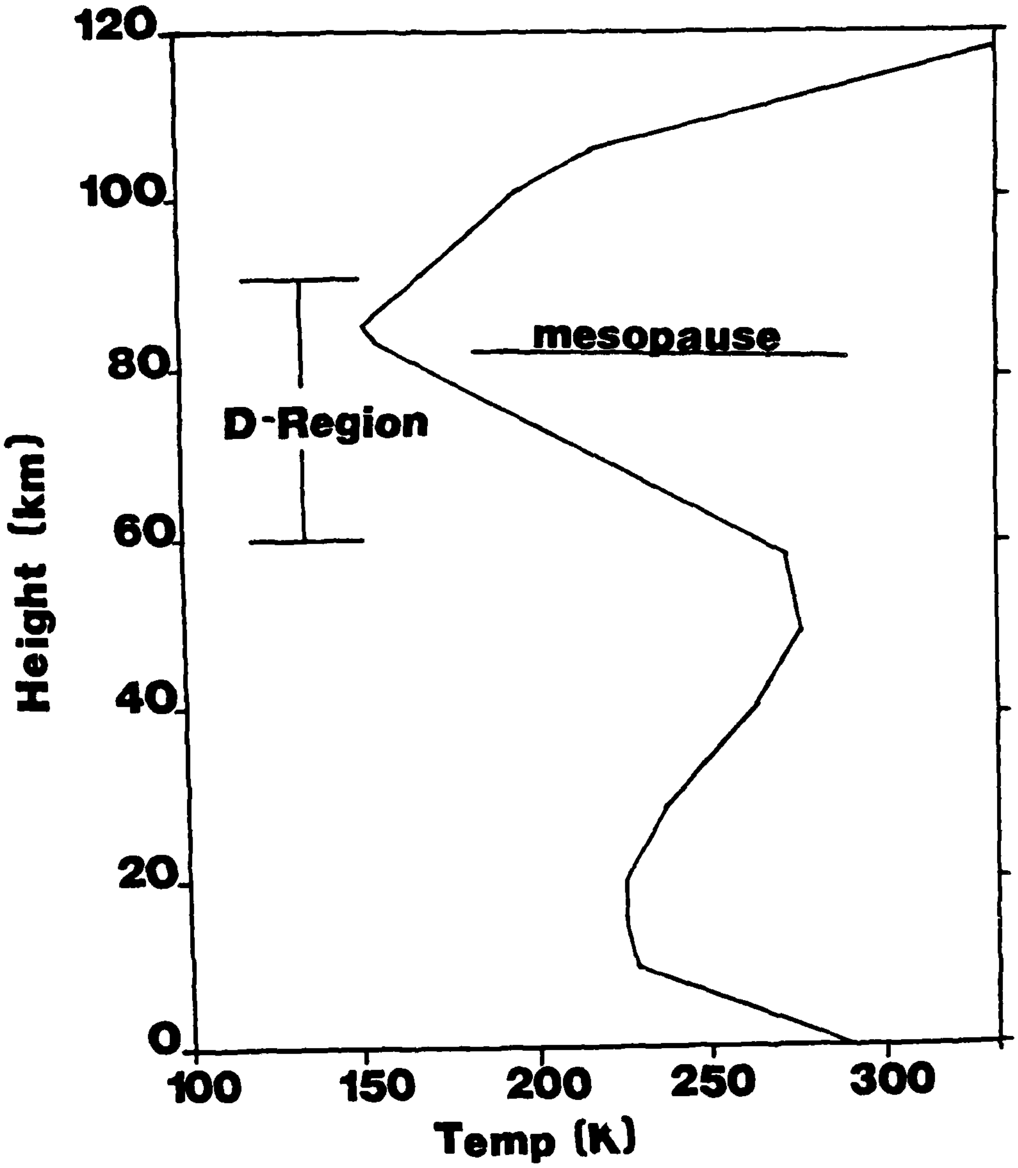


Figure 1 High latitude, summer, vertical temperature profile. Note the extremely cold environment of the high latitude summer mesopause (data from U.S. Standard Atmosphere, 1966).

1.2 The Basics of NLC/PMC and Aurorae

1.2.1 Noctilucent Clouds (NLC)

Noctilucent clouds (NLC) have been studied for a century, yet the nature and origion of these clouds are still uncertain. Noctilucent cloud formations are the highest ones known to exist in the atmosphere, forming at an average altitude of 82.7 km near the summer mesopause at high latitudes. They are tenuous scattering features containing wavelike structures with a vertical amplitude range of 1.5 to 3 km and a thickness of 0.5 to 2 km (Fogle and Haurwitz, 1966). NLC are seen because they scatter sunlight, primarily in the forward direction (Avaste et al., 1980). To be observed from the ground, there should be no low-level (tropospheric) cloud cover obstructing vision, the 82 km region must be sunlit and the sky background must be dark. Thus, observations of NLC are confined to periods during which the sun is low enough so the background sky is dark, yet high enough to illuminate the NLC level. Fogle and Haurwitz (1966) state that these conditions occur when the sun is about 6-16° below the horizon; optimum illumination occurs when the sun is 9-14° below the horizon. Due to solar illumination conditions and the need for extremely low mesopause temperatures, NLC can only be seen in a latitude range of about 50-70°, with the best viewing location at about 60° (Fogle and Haurwitz, 1966). NLC often appear bluish-white in color and are observed from March through October, although June through August are the best viewing months (Fogle and Haurwitz, 1966). These clouds have been observed to occupy areas as small as 10,000 km^2 to more than 4,000,000 km^2, last for several minutes to more than five hours, have apparent phase velocities averaging 40 m/s and exist in cold regions that have temperatures of about 135K (Fogle and Haurwitz, 1966). Review articles on NLC are Fogle and Haurwitz (1966), Avaste et al. (1980) and Gadsden (1982).

1.2.2 Polar Mesospheric Clouds (PMC)

Airglow photometer measurements on board the OGO-6 satellite led to the discovery of a particulate scattering layer at about 85 km which forms over the local summer geographic pole (Donahue et al., 1972). Observations made with the ultraviolet spectrometer (UVS) on board the SME satellite confirmed the existence of this phenomenon. The scattering layer, referred to as polar mesospheric clouds (Thomas, 1984), is a consistent feature of the summer polar mesopause; it extends from the usual NLC viewing conditions (roughly 50-70°) all the way to the summer pole and has an estimated thickness of 5 km (Donahue and Guenther, 1973). Data from SME indicates that polar mesospheric clouds (PMC) are made of discrete, bright patches separated by a weaker, persistent background (Thomas, 1984). This change in brightness is thought to be due to small changes in particle radii caused by wind and temperature changes associated with gravity and/or tidal wave action; the larger the radii, the brighter the appearance. This is consistent with NLC observations which indicate the clouds contain wavelike structures (Fogle and Haurwitz, 1966). Olivero and Thomas (1986) use SME data to discuss the climatology of PMC. They found that the brightest PMC are located where PMC occur most frequently - above 70° in latitude and in a season confined to

+/- (25-30) days about the peak (which is 20 to 30 days after the summer solstice). This is approximately true for both hemispheres; they also noted that PMC in the Northern Hemisphere are inherently brighter (larger particle radii) than those in the Southern Hemisphere. Using SME data, Thomas (1984) estimated the upper limit of PMC particle radius to be 0.07 μm.

PMC, like NLC, appear in both northern and southern hemispheres. However, PMC occur above the continuously sunlit polar cap and extend equatorward whereas NLC are generally observed from 50 to 70°. Like NLC, PMC are tenuous scattering features, although PMC are much brighter than NLC. But PMC are visible only from above the lower atmosphere (because of competing solar illumination of the troposphere at those latitudes) while NLC, located outside the continuous sunlight zone, are visible from the ground and space. Polar mesospheric clouds are also more optically intense than noctilucent clouds, increasing their optical depth by 50 to 100 times between 65 and 80° latitude (Donahue et al., 1972). This may be due to the greater vertical thickness in PMC (5 km versus 0.5 to 2 km for NLC). Hence, it has been suggested that PMC are compositionally similar to NLC, but that NLC are actually the sporadic, visible extensions of this more permanent polar cap phenomenon to lower latitudes where viewing conditions are more favorable (Donahue et al., 1972). In his analysis of SME data, Thomas (1984) reported a steep latitudinal variation in PMC occurrence. He found that PMC layer to be sporadic in the 50-60° zone, which agrees with NLC behavior; in the 70-80° zone, PMC were found to be "ubiquitous." From here on, PMC will refer to the permanent polar cap scattering layer detected by instruments or seen from above the lower atmosphere within the zone of continuous sunlight (about 70-90°) while NLC are the visible extensions of this scattering layer seen from roughly 50-70°.

1.2.3 Aurorae

The mesopause region is not only a niche for PMC and NLC, but also for other important atmospheric phenomena such as the ionospheric D-region, the lower boundary of meteoric phenomena and the lower boundry of aurorae. Before discussing the aurora, one must first explain the solar wind. The solar wind has its origins in the sun's corona, which is a gas with a temperature of about 10^6K (Brasseur and Solomon, 1984; see Figure 2). Although the sun has an extremely large gravitional field, the hot gas has enough kinetic energy so that particles can stream outward constantly and in all directions from the sun. The solar wind consists mainly of hydrogen. But at such high temperatures the hydrogen is ionized, so the solar wind is actually a plasma of protons and electrons flowing at speeds anywhere from 300 to 1000 km s^{-1}, depending on solar activity (Beer, 1976). Thus, generally, the aurora is created by high speed electrically charged particles contained in this solar wind which enter the earth's magnetosphere and penetrate the atmosphere along magnetic field lines. There, these high energy solar particles collide with numerous atmospheric molecules; the collisions excite these molecules, which then emit light which we perceive as the aurora. As we shall see later in this paper, energetic electrons from Type B aurorae (Beer, 1976)

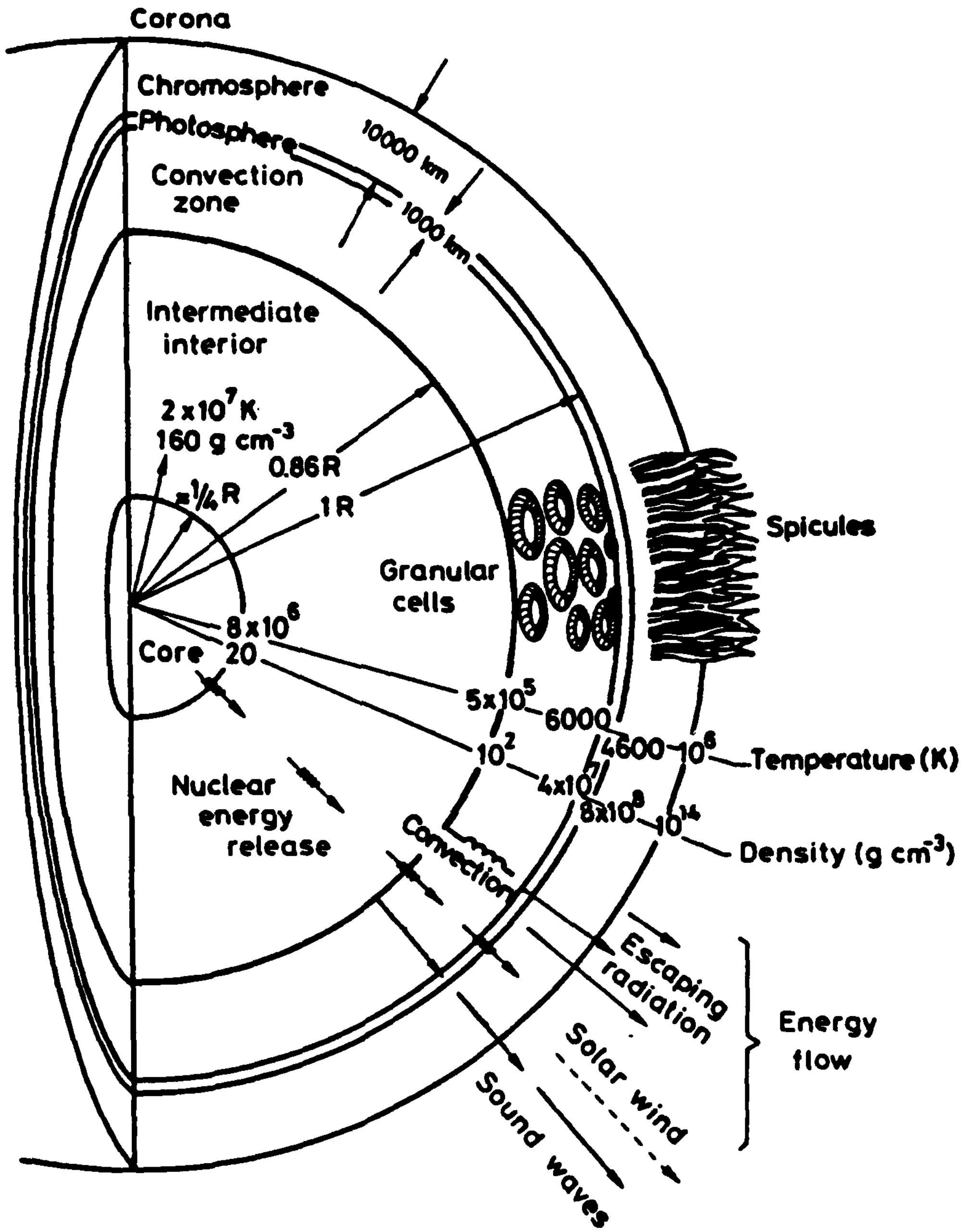


Figure 2 Schematic diagram of the solar atmosphere (from Brasseur and Solomon, 1984). Note the corona, which is the region immediately above the chromosphere. The corona's temperature is roughly 10^6K. Also note the solar wind - a plasma consisting of protons and electrons, emanating from the corona, which can travel at speeds up to 1000 km s^{-1}.

can precipitate down to about 80-85 km causing the exicited molecules to emit light at this altitude - which is also the NLC/PMC altitude.

1.3 The Question of Inter-Relationship

Smyth (1886) and Backhouse (1886) were the first to observe aurorae simultaneously with NLC (Fogle and Haurwitz, 1966). Fogle (1966) observed aurorae and NLC together on 13 nights. On seven nights, they were in the same part of the sky and the intensity of the clouds was observed to decrease; on two nights, the clouds vanished. Fogle and Haurwitz (1966), like D'Angelo and Ungstrup (1976), suggested auroral heating at or below the mesopause causes this effect. Paton (1973) and McIntosh and Hallissey (1975 and 1980) reported simultaneous occurrences of NLC and aurorae over W. Europe in the summers of 1972, 1974 and 1979 respectively. Since energetic particles can penetrate the atmosphere down to NLC/PMC altitudes, it seems reasonable to infer that auroral activity can affect upper mesospheric dynamics by, for example, increasing the temperature and ionization in that region, which in turn could affect wind patterns, chemical composition and other parameters. Thus, there is probably some sort of coupling between the occurrence and intensity of aurorae and the frequency of occurence of NLC/PMC; this is the problem we shall investigate.

1.4 Statement of Problem

The purpose of this paper is to build on the ideas of Fogle and Haurwitz (1966), D'Angelo and Ungstrup (1976) and others who have suggested that the occurrence of NLC and PMC may be anticorrelated with auroral activity and the related high levels of geomagnetic activity. This paper will review PMC, NLC and aurorae and then discuss a number of ways in which these phenomena may be coupled.

2.0 THE NLC/PMC PHENOMENA

2.1 Observations

The earliest recorded observations of NLC came after volcanic dust from the Krakatoa eruption (1883) spread over the earth creating magnificent sunsets (Fogle and Haurwitz, 1966). The effect this eruption had on the atmosphere caused scientists to observe the sky more intensely. In 1885, Backhouse made the first observations of NLC noting their unusual height; Tseraskii of Russia and Jesse of Germany were the first to rigorously study them in 1885 (Fogle and Haurwitz, 1966). Jesse created the term "Leuchtende Nachtwolken," from which we get (roughly) "noctilucent clouds." He also made the first accurate height measurements. Using photographic triangulation, he found the clouds to be at an altitude of about 82 km - approximately the height of the mesopause. Vestine made the first NLC observations over N. America and published the first major work on the clouds (Vestine, 1934).

2.1.1 General

The highest and lowest latitudes where NLC have been reported over N. America are 71.3N and 45.5N respectively (Fogle and Haurwitz, 1966). The maximum frequency of NLC is centered around 60° latitude. However, longitudinal variation is more interesting. According to Fogle and Haurwitz (1966), Sharonov (1965) reported a possible longitudinal variation in NLC frequency (an increase in frequency from east to west). Fogle and Haurwitz (1966) reported a similar experiment but found no variation. But Fogle (1966) reported there may be a longitudinal effect from 0E to 140W; this is the area in which the auroral zone crosses the maximum zone of NLC occurrence. If a mesopause temperature of 135K is a requirement for NLC formation, and if the mesopause in the auroral zone is heated during times of strong geomagnetic activity (as is currently believed), then there may be fewer NLC displays from 0E to 140W than at other longitudes. This may lead to an anticorrelation between the frequency of NLC occurrence and the geomagnetic activity level. This longitudinal variation plays an important role in how one analyzes worldwide data as well. In N. America, for example, the auroral zone exists at latitudes where NLC are frequently observed. As Gadsden (1984) points out, the auroral zone in W. Europe is north of the NLC latitudes. He concludes this difference may affect the frequency of occurrence of NLC between the European and N. American sectors.

2.1.2 Ground-Based

Fogle and Haurwitz (1966) reported that before 1962, few NLC observations were reported from N. America whereas hundreds of observations had been reported from Europe and the USSR where a network of observing stations already existed. Scientists began to wonder if there were some physical mechanism(s) which prevented NLC from forming as often in the West as over W. Europe and the USSR (such as the auroral zone in N. America crossing the maximum NLC occurrence zone). To examine this question, and others about NLC, a study of NLC over N. America was started in 1962. Arrangements were made to have routine observations of NLC made at meteorological stations in Canada and

Alaska, similar to those already done in W. Europe and the USSR. Information from this network of observating stations indicate that NLC do occur frequently over N. America (Fogle and Haurwitz, 1966). They go on to suggest that the previous lack of data from N. America was probably a result of few interested and informed observers there.

2.1.3 Space-Based

Avaste et al. (1980), summarized some space data from Salyut missions and found that in the summer, NLC often completely cover the latitude belt north of approximately 45°. He also found similar NLC fields in the Southern Hemisphere, although they were shifted more southward to about 53°S. Photometric data confirmed that these NLC fields consisted of particles with radii slightly greater than 0.1 μm and from his data he assumed Southern Hemisphere; this agrees with the findings of Olivero and Thomas (1986). Avaste et al. (1980) also reported observing complex NLC structures with two and three level NLC fields existing.

Synoptic data from SME is now available. This data verifies earlier observations by Donahue et al. (1972) that a scattering layer (PMC) extends from the usual NLC viewing conditions (50 to 70°) all the way to the summer pole. However, a problem with SME is that it "sees" little below about 70° latitude; thus, one cannot detect NLC with these observations, only PMC (Olivero, personal communication, 1986).

2.2 Theory

After a century of ground-based observations, occasional in situ rocket probing and recent satellite measurements, the physics of NLC/PMC is still questionable. Cloud microphysics, atmospheric dynamics and the general circulation at that height add to the complexity of understanding these clouds. Current NLC/PMC formation theories suggest the clouds consist of ice particles formed near the mesopause by water subliming on nucleating agents. All of these theories require a sufficiently cold high-latitude summertime mesopause, a sufficient amount of aerosols or ions near the mesopause to act as nucleating agents and a supersaturated environment so water vapor can sublime onto these cloud nuclei.

2.2.1 NLC/PMC Particle Composition and Size

It is believed that the particles in NLC/PMC consist of ice with either metallic nuclei of extraterrestrial origin (Hesstvedt, 1961), or complex ion nuclei (Witt, 1969). Olivero and Thomas (1986) suggest that the main reason for inferring that they consist of water ice particles is because NLC/PMC are associated with very cold air in the summer polar mesopause region. In situ temperature measurements (Theon et al., 1967), with NLC present above Pt. Barrow (71N), indicated temperatures between 130-140K at mesopause heights. This low mesopause temperature has led to an increasing acceptance of the ice-cloud hypothesis.

Particle sampling, to determine the cloud's composition, has been attempted several times with inconclusive results. In 1971 and 1973, a series of rocket-borne sampling experiments were launched into NLC displays over Sweden. An electron microscope analysis of the collected particles indicated more than 30 elements (nickel and iron included) which were probably of extraterrestrial origin (Hallgren et al., 1973). Estimates of NLC number density, using in situ particle collectors, yeilded concentrations of $10^3 m^{-3}$. Polarization and brightness techniques indicated concentrations of $10^6 m^{-3}$ (Tozer and Beeson, 1974). The optical data suggested the particles were either solid ice or a nucleus with an ice coating. Nearly 98% of the particles were determined to have radii less than 0.13 μm (Tozer and Beeson, 1974). The cloud's number density difference found between rocket samples and optical methods led Tozer and Beeson (1974) to conclude that either a large number of particles went undetected or a large number of cloud particles are the result of nucleation on complex ions. This complex ion nucleation was first proposed by Witt (1969) who tried to sample mesospheric dust particles which might act as ice nuclei; only a small number were detected. This led him to suggest that NLC particles may form on complex ions and that proton hydrates would be the most probable family of ions to grow to large sizes; he speculated that the hydration of Fe^+ may be a possible nucleation mechanism for NLC particles. This theory has been supported by the findings of Goldberg and Witt (1977) in which mid and high latitude ion composition measurements were compared. Goldberg and Witt found a presence of Fe^+, its oxides and hydrates above 80 km in high latitude data; these heavy ion clusters were not found in mid-latitude data. Below 80 km, the high and mid-latitude data showed the ion composition to be similar.

Goldberg and Witt concluded that these heavy clusters may act as condensation nuclei for ice crystal growth in the cold mesosphere. Note that the presence of Fe^+ between 80-100 km can be explained by meteor ablation; Goldberg and Witt (1977) report that most meteoric showers deposit meteoric material between about 85-100 km. Bjorn et al. (1985) have results that also support the idea that ion nucleation may occur in the altitude region around the arctic summer mesopause. They identified proton hydrate ions up to the 12th order of hydration and an ion mass distribution up to about 360 amu, which corresponds to proton hydrates with 20 H_2O molecules. They went on to report the thickness of this layer was less than a few hundred meters and the existence of such heavy ions reflects the low electron density in combination with a very low temperature and high H_2O_v concentration - parameters needed for NLC/PMC formation.

Sizes of NLC/PMC particles are also uncertain because of the lack of necessary data at the summer polar mesopause and the difficulty of accurately measuring in situ particle sizes; consequently, theories on NLC/PMC generation are questionable. NLC/PMC particle sizes have been theorized to be in the range of 0.05 - 0.13 μm, but there are problems with interpreting data from direct sampling and optical scattering measurements (Thomas and McKay, 1985). As an example, the polarization data of Tozer and Beeson (1974), which is often quoted in the literature, can be interpreted in terms of small particles with sizes < 0.13 μm or large sizes > 0.3 μm (Gadsden, 1978). Bohren (1983) reported that polarization studies show the particles to be not much larger than 0.1 μm. Hummel and Olivero (1976), using the satellite radiance measurements of Donahue et al. (1972), arrived at an upper limit of about 0.13 μm; this is similar to the findings of Witt (1969) and Tozer and Beeson (1974). The most recent results (and the most widely accepted) are those of Thomas (1984) who gives a particle radius of 0.07 μm as the upper limit. Still, there is no consensus in the literature on the characteristic size of the NLC/PMC ice particles.

2.2.2 NLC/PMC Formation Theories

Several noctilucent cloud models have been devised. The suggestion that NLC consist of ice crystals was first proposed by Humphreys in 1933. This theory was not accepted because the temperature at the mesopause was believed to be too high for saturation to occur. But Murgatroyd (1957) and Murgatroyd and Singleton (1961) modeled the atmosphere and found atmospheric temperature minimum to be at the high latitude summer mesopause. They noted that this high latitude summer region is cooled by rising air between 50-80 km which has upward vertical velocity of about 1 cm s^{-1}. Hesstvedt (1961) then revived Humphreys' theory and suggested that NLC could be ice clouds; he discussed the physics of ice cloud formation in the mesosphere and illustrated how meteoric dust could be the sublimation nuclei. Fiocco and Grams (1971) investigated meteoric ablation and its effects on NLC formation; they suggested that NLC formation could begin with the sublimation of moisture on extraterrestrial dust. Hunten et al. (1980) calculated the amount of dust present at mesopause heights due to meteor ablation. They showed that much of the meteoric material is deposited between 75-90 km and hence suggested that this process may be an important source of nuclei for NLC.

As mentioned earlier, Witt (1969) postulated that hydrated ions (and on meteoric dust particles) were the nuclei for NLC. He suggested that ion nucleation could occur in NLC; Goldberg and Witt (1977), Bjorn and Arnold (1981) and Bjorn et al. (1985) reinforced his hypothesis by obtaining measurements of large hydrated ions near the summer polar mesopause. Bjorn and Arnold (1981) reported that the most massive proton hydrates were concentrated at about 90 km (hydrates with 20 water molecules); they suggested that these large particles at 90 km could eventually gravitationally fall to NLC heights where water vapor subliming onto their surfaces could lead to visible NLC.

Turco et al. (1982) created a microphysical model from which they concluded that likely condensation nuclei are meteoric dust or, if the temperature is less than 130K or if dust is absent, the nuclei could be large H_2O cluster ions. The formation of NLC/PMC particles by either nucleation mechanism requires a time scale on the order of 12-24 hours. Hence, an important condition for NLC/PMC formation is an extremely cold mesopause. Turco et al. (1982) showed that under these cold conditions, the initial high rate of nucleation reduces the supersaturation to where further nucleation ceases. Additional growth occurs by sublimation, causing the mean particle size to increase with time. They went on to report that an upward convective velocity of about 1 cm s^{-1} probably exists in NLC/PMC regions and that gravity waves can modify the cloud intensities with rapidly propagating gravity waves ($u > 10$ m s^{-1}) dissipating the NLC/PMC.

Schilling (1964) and McDonald (1964) used thermodynamics to define existence regions for small ice particles in the upper atmosphere. The conditions used in their work was that an ice particle cannot continue to exist if $e_i < e_s$ where e_i is the ambient water vapor pressure and e_s is the saturation vapor pressure over ice particles, which depends on particle temperature and radius. Their results show that ice particles can only exist in and near the summer polar mesopause; this finding helped to further advance the ice cloud hypothesis. Grams and Fiocco (1977) used an equilibrium particle temperature model to study ice spheres. They found that above 80 km, the ice particle temperature exceeds that of the ambient temperature. They went on to determine exclusion limits for ice; like Schilling and McDonald, they found the summer polar mesopause to be the most favorable region for ice particle persistence. Bevilacqua (1978) defined existence regions for ice particles as those regions of the atmosphere in which the particles can either grow or persist. He also concluded that ice particles can only exist in and near the summer polar mesopause.

Christie (1969) studied dynamics in relation to NLC genesis. He suggested vertical turbulent diffusion carried H_2O_v into the NLC region and that increases in these turbulent diffusion rates were associated with the propagation of gravity waves through the mesosphere and that NLC displayed structural characteristics of these gravity waves. He also found that large amplitude gravity waves heat the mesopause through turbulent energy transfer.

Reid (1977) suggested that if cloud particles are smaller than 0.13 μm, then the water ice content can greatly exceed the atmospheric water supply. To circumvent this problem, Reid suggested that the particles be non-spherical. These non-spherical ice particles could fall through the mesopause slowly enough to achieve sizes which would be optically observable in the NLC/PMC layer. Bohren (1983) suggested that no matter what shape the NLC particles might be, polarization studies indicate them to be randomly oriented. Bjorn et al. (1985) suggested that the cause of NLC/PMC might be changes in the energy balance of the upper stratosphere, possibly caused by variations in O_3 heating, or changes in the dynamic coupling between the stratosphere and mesosphere, possibly through increased gravity wave activity.

Although it is generally assumed that NLC/PMC consist of ice particles, the mechanism by which NLC/PMC form is not agreed upon or fully understood.

2.3 Water Vapor in the Mesosphere and its Effects on Cloud Formation

To successfully model NLC/PMC, the amount of water vapor in the mesosphere must be considered. Sparse measurements and contradictory data make water vapor concentrations at the mesopause an uncertainty. Observations of water vapor above 40 km are few in number because of numerous difficulties associated with in situ and remote sensing techniques. Avaste et al. (1980) reports that episodic measurements of water vapor in the mesosphere show a scatter of data as large as two orders of magnitude. They suggest this may be caused by the different methods of measurement. However, measurements taken within the past few years are thought to be fairly indicative of the true concentrations.

Scientists here at The Pennsylvania State University are associated with some of the best mid-latitude water vapor in the mesosphere measurements in the world. Recently, researchers at the

Naval Research Laboratory (NRL) and Penn State have used the radio astronomy facilities of the Haystack Observatory (latitude 42° 37', longitude 71° 91') to estimate the mesospheric water vapor profile using ground-based spectral line measurements of the 22.2 GHz H_2O_v emission line (Schwartz et al., 1983; Bevilacqua et al., 1983; Olivero et al., 1986). The findings of Schwartz et al. (1983) and Bevilacqua et al. (1983) indicate that the water vapor profile is constant (or slowly increasing with height) in the stratosphere and then eventually reaches a maximum of 5-8 ppmV at about 65 km. The mixing ratio then decreases rapidly to about 1 ppmV at 85 km (Bevilacqua et al., 1983). Measurements below about 65 km are in agreement with other mesospheric water vapor measurements and photochemical model calculations (Bevilacqua et al., 1983). But the rapid mixing ratio falloff with height above 65 km is much greater than that derived from photochemical model calculations (Olivero et al., 1986; Bevilacqua, 1983). Some high latitude summertime microwave measurements have been made, but the results are questionable. Photochemical models of the water vapor mixing ratio at these summertime high latitudes can give values anywhere from a few tenths to 5 ppmV.

In addition to this joint research between NRL and Penn State, The Pennsylvania State University has also constructed a 22-GHz radiometer which is dedicated solely to water vapor observations from the main campus of Penn State. Recent results from Penn State (see Olivero et al., 1986) are similar to the findings of Schwartz et al., 1983 and Bevilacqua et al., 1983, although somewhat drier; Olivero et al. (1986), for example, report about 0.5 ppmV at 80 km.

The normal distribution of water vapor in the atmosphere can explain all cloud types except NLC/PMC (Beer, 1976). At 80 km, water vapor is photodissociated: H_2O_v + hv (< 0.24 μm) → H + OH. This reaction decreases the amount of water vapor content below the level needed to produce clouds. Other possible sinks of water and water vapor at the mesopause include sedimentation (larger water clusters are gravitationally removed) and transport of water vapor out of a possible cloud region by meridional winds (Young, 1979). Hence, a mechanism is needed which either transports water vapor back up into the NLC/PMC region or which acts as an in situ source of water vapor so the clouds can form. The following discussion will examine this upward transport of water vapor and possible in situ source, and their possible effects on NLC/PMC formation.

We have noted that the meridional mesospheric circulation system is controlled by an upwelling of air over the high latitudes of the summer hemisphere and balanced by a downward motion of air over the winter high latitude region. This circulation is driven by solar heating in the ozone layer around the stratopause of the high latitudes of the summer hemisphere. This vertical transport, enhanced by an increased mesospheric updraft, may be the mechanism supplying enough water vapor to the NLC/PMC region to support cloud genesis (see Figures 3,4). Young (1979) demonstrated that this upward motion is capable of transporting sufficient amounts of water vapor into the mesosphere to support particle distributions with all particle radii

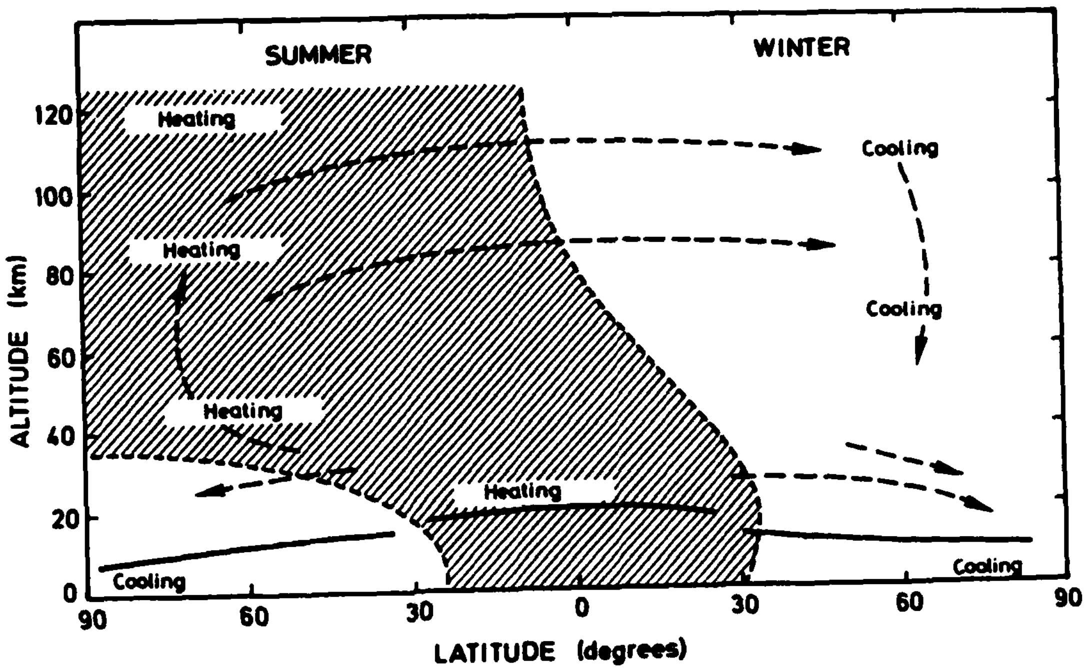


Figure 3 Meridional circulations in the summer and winter hemispheres (from Brasseur and Solomon, 1984). Note the rising motion in the high latitude summer mesosphere. This mesospheric updraft may be the mechanism by which water vapor is supplied to the NLC/PMC region, thus supporting cloud genesis.

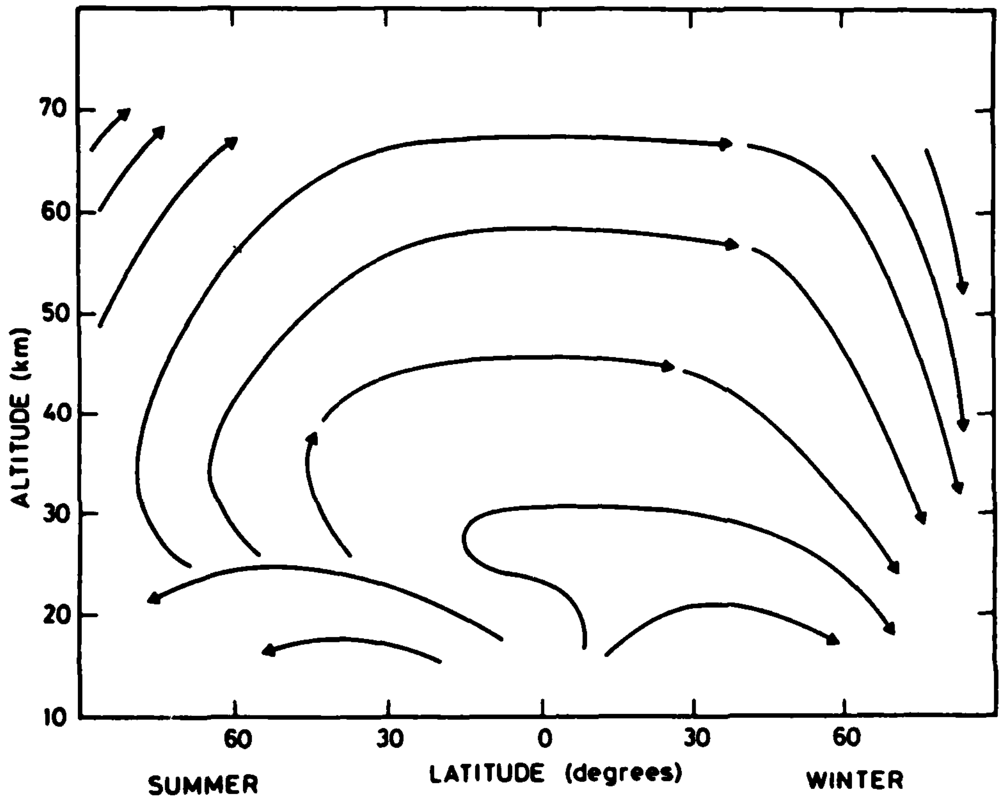


Figure 4 Streamlines of the diabatic circulation in the summer and winter hemispheres (from Brasseur and Solomon, 1984).

less than 0.1 μm. Solomon et al. (1982) and Garcia and Solomon (1985) modeled mesospheric water vapor and predicted that at about 80 km, the mixing ratio would fall off with height due to photodissociation with a minimum water vapor concentration at summertime. They expected water vapor values at the high latitude summer mesopause to be a few tenths to 3 ppmV. This model information on water vapor, along with the recent microwave measurements and our knowledge of temperature and other parameters at this level, indicates that supersaturation could occur frequently at the summertime high latitude mesopause. Thus, NLC/PMC could form by H_2O_v subliming onto either meteoric dust or water cluster ions, which would further advance Humphreys' ice cloud hypothesis. But rapid nucleation may not necessarily mean that a visible cloud will form; the new cloud particles must survive long enough so they can grow to a size where they scatter light effectively enough to be seen. For this to happen, there must be a large enough water vapor pressure for the particle to grow before it falls out of the saturated region, and the layer directly beneath the nucleating layer must be wet enough to allow the particles to grow (Gadsden, 1982).

Thus let us assume that the NLC/PMC particles are ice. As these ice particles grow larger and larger, to observable sizes, they may gravitationally fall through the cloud region and sublime upon leaving this existence region (Bevilacqua, 1978) forming a potential reservoir of water vapor near the bottom of the existence region. The vertical transport discussed by Young (1979) would then transport some of this water vapor back up into the NLC/PMC region allowing the process of ice particle nucleation to begin again. This feedback mechanism could lead to NLC/PMC enhancement, unless strong meridional winds were present which could impede the vertical flux of water vapor into the cloud region.

A very different picture of upper atmospheric water vapor is suggested in two separate papers by Frank et al. (1986). In these papers, they report an influx of comet-like objects into the earth's upper atmosphere. They envision these small comets to consist of a fluffy aggregate of water snow and dust. They noted that the mass of each of these objects is about 100 tons and that there are about 4×10^{30} molecules per comet (a diameter of roughly 12 m). The average global cometary water vapor influx was calculated to be about 3×10^{11} molecules per cm^2 per sec corresponding to about 20 cometary events per minute. They went on to show that the total mass influx into the atmosphere due to these comets is roughly 10^{12} kg per year. For comparison, they noted that the mass of meteoric material swept up by the earth is about 10^5 to 10^7 kg per year. A minimum altitude for atmospheric penetration was calculated at about 125 km; thus, they concluded that water molecules could not directly penetrate below about 100 km. However, turbulence, diffusion and advection could transport the comet particles to lower altitudes, i.e., the mesopause. The possible injection of water and dust into the upper atmosphere by comet-like objects is an intriguing new hypothesis. It may behave as an in situ source of water vapor thereby assisting in NLC/PMC formation. Or, this comet influx may be responsible for the deposition of large amounts of dust upon which water vapor already present sublimes.

3.0 THE AURORA AND ITS POTENTIAL IMPACT ON NLC/PMC

3.1 General Characteristics of Aurorae

Unlike NLC, which have only been studied for the past 100 years, the aurora is one of the oldest known geophysical phenomenon. Anaximenes discussed them in 590 BC and Aristotle (330 BC) called them "chasms" inferring he thought them to be cracks in the sky through which flames could be seen (McCormac, 1967). Generally speaking, the aurora is created by high speed, electrically charged particles contained in the solar wind which enter the earth's magnetosphere and penetrate the atmosphere along magnetic field lines. There, these high energy solar particles collide with numerous atmospheric molecules; the collisions excite the molecules which then emit light.

Lorentz forces, in a uniform magnetic field, cause electrons and protons to move in circles in opposite directions (Hones, 1986). If, for example, a particle's motion has a component parallel to the magnetic field's direction, the Lorentz forces will cause the particle to follow a helical trajectory, with the center of this trajectory tracing out a magnetic field line. Hence, charged particles can be visualized as being tied to magnetic field lines (Hones, 1986). The charged particles of the solar wind which enter the earth's magnetosphere therefore spiral down into the atmosphere about magnetic field lines. When an electric field (E) is applied perpendicularly to a magnetic field (B), the particles tied to the magnetic field lines will drift perpendicularly to both E and B. Positive and negative particles will drift with the same velocities, allowing for particles in a plasma (such as the solar wind) to all drift together (Hones, 1986).

The interplanetary magnetic field, originating at the sun, has been observed to point either towards or away from the sun (Beer, 1976). This field also has small east-west and north-south components. The north-south component is very important in understanding auroral events. Normally, the component is northward (Beer, 1976), and electrical energy generation due to the solar wind interacting with the earth's magnetic field is a minimum (Hones, 1986). But when the component is southward, the flow of electrical energy increases and there are magnetic storms, ionospheric storms and an increase in aurorae. This happens because with a southward component, the interplanetary magnetic field connects with the earth's magnetic field, and there are then two ways in which solar plasma can penetrate the magnetosphere and arrive at the poles. First, these particles may precipitate down the connected field lines in the polar cusp region to produce Type A aurorae or secondly, they may be accelerated from the magnetotail to the polar regions producing Type B aurorae (Beer, 1976). Type A aurorae have electrons with energies of about 100 eV and produce a red emission at 0.63 μm in the 150-400 km range (Beer, 1976). Type B aurorae have more energetic electrons (energies > 100 keV) and produce aurorae in a variety of colors. Due to the greater energy of the precipitating auroral particles, Type B aurorae extend downward to as low as 80-85 km.

From a physical standpoint, the aurora has been better observed than NLC/PMC; it has been seen between 70-1000 km in altitude with an average height of around 100 km. Auroral regions are defined as those parts of the earth between 60° geomagnetic (gm) latitude and the geomagnetic poles. Sub-auroral regions are from 45-60° gm latitude and the min-auroral regions are from 45N-45S gm latitude (Petrie, 1963). Furthermore, the auroral region is divided into three parts: the auroral oval, zone and cap (see Figure 5). Precipitating auroral particles travel to polar regions along magnetic field lines; hence, the auroral oval is that part of the upper atmosphere which intersects with the part of the magnetosphere from which auroral particles come. The solar wind distorts the magnetosphere, causing field lines to be close to the earth's surface on the dayside and drawn away on the nightside (see Figures 6a,b); thus, the auroral oval gets its characteristic shape. The oval remains fixed while the earth beneath it rotates forcing some areas to leave the oval yet bringing other areas in. The area the auroral oval sweeps out as the earth rotates beneath it is basically annular about the geomagnetic pole and is called the auroral zone; this is the area in which displays are most frequent. At about 68° gm latitude, (see Figure 7), there is a 100% frequency of aurorae (Petrie, 1963). Obviously, this auroral zone is not static - it varies with the geomagnetic activity level. The number of sunspots, for example, is known to affect the geomagnetic latitude of maximum auroral frequency. Thus, the auroral zone covers an area from roughly 55-75° gm latitude with the frequency of displays decreasing poleward and equatorward. However, auroral displays have

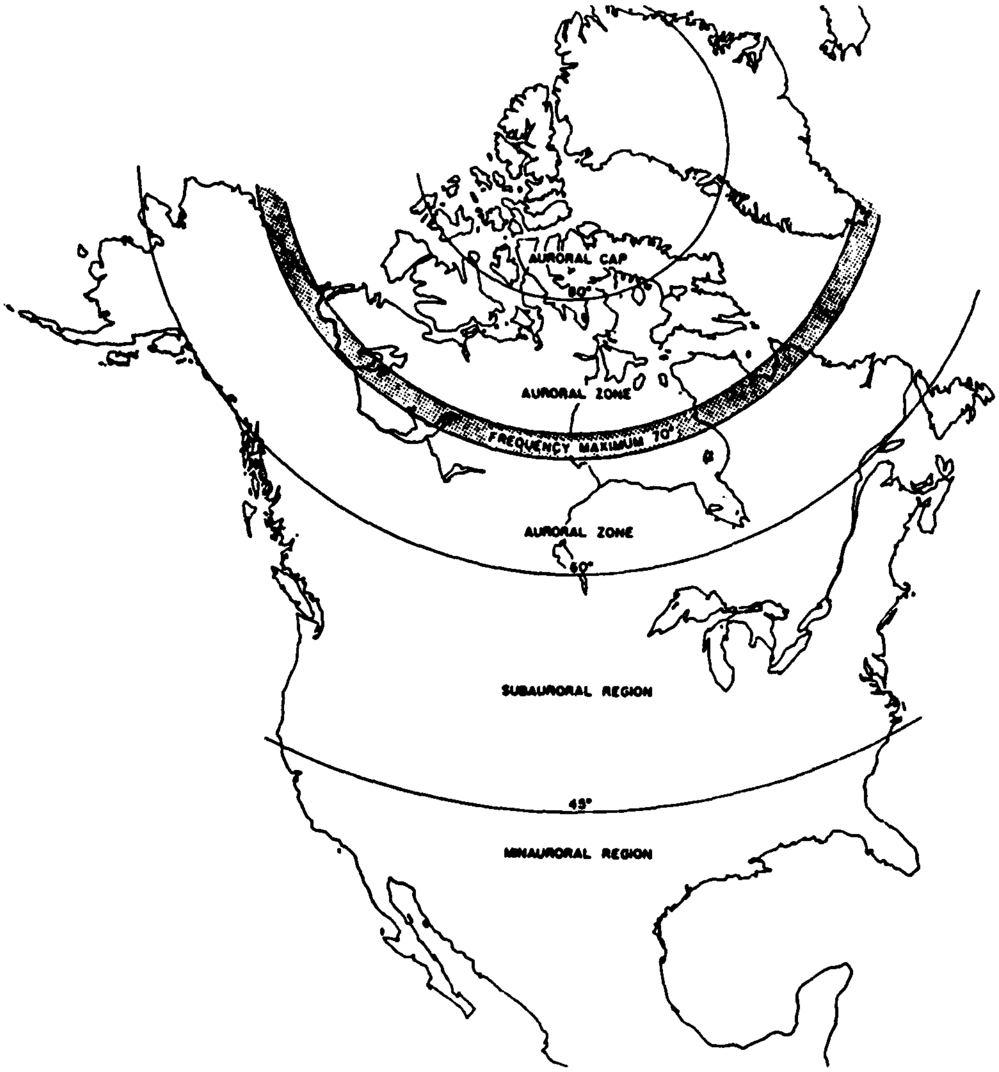
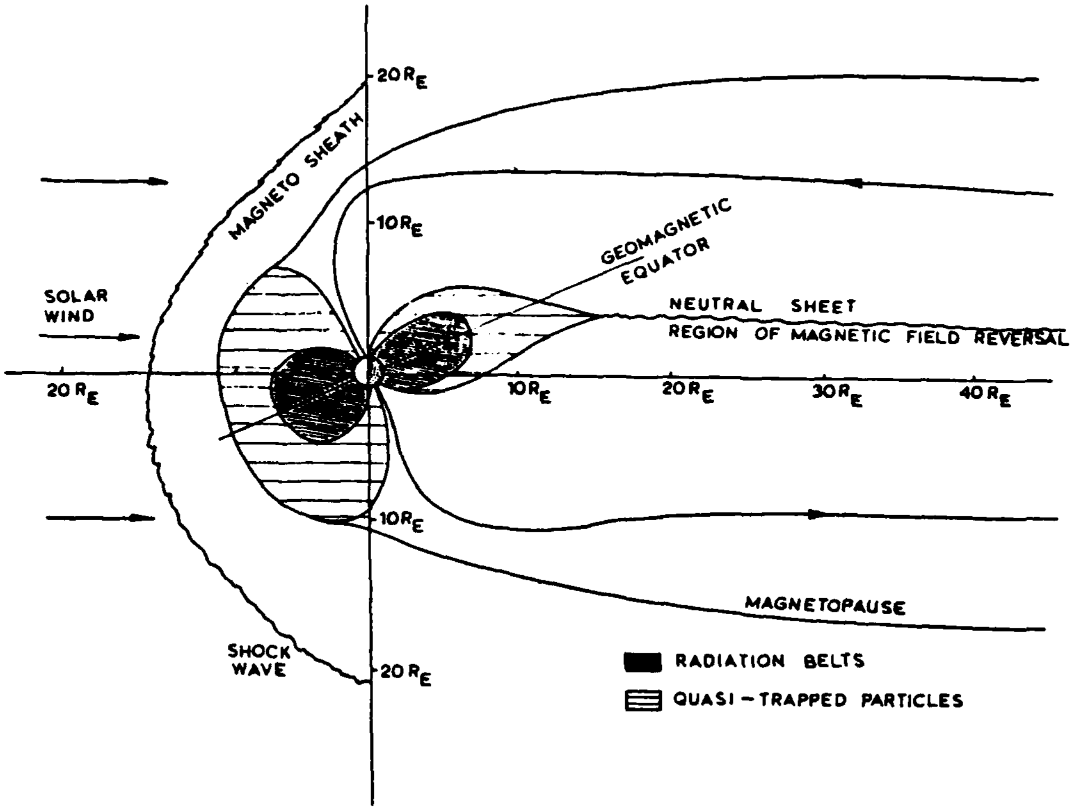


Figure 5 The Auroral Zone and other regions across North America (from Petrie, 1963). Latitudes are in geomagnetic coordinates, not geographic.



Figures 6a,b Magnetospheric distortion caused by the solar wind (from Beer, 1976). Figure 6a (above) shows that the earth's magnetosphere is distorted because of its interaction with the solar wind. The earth's magnetic field appears flattened on the dayside, yet elongated on the nightside. Figure 6b (next page) shows the magnetic field lines. When this field has a southward component, there are magnetic storms, ionospheric storms and an increase in aurora (Beer, 1976).

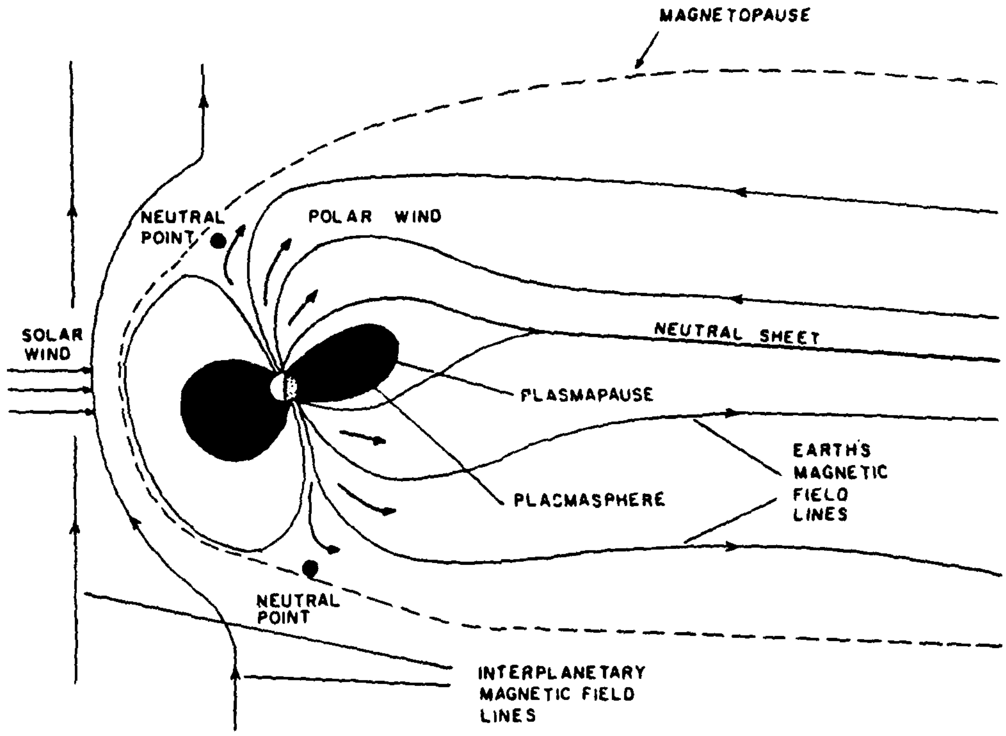

MAGNETOPAUSE
NEUTRAL POINT
POLAR WIND
SOLAR WIND
NEUTRAL SHEET
PLASMAPAUSE
EARTH'S MAGNETIC FIELD LINES
PLASMASPHERE
NEUTRAL POINT
INTERPLANETARY MAGNETIC FIELD LINES

Figure 6b

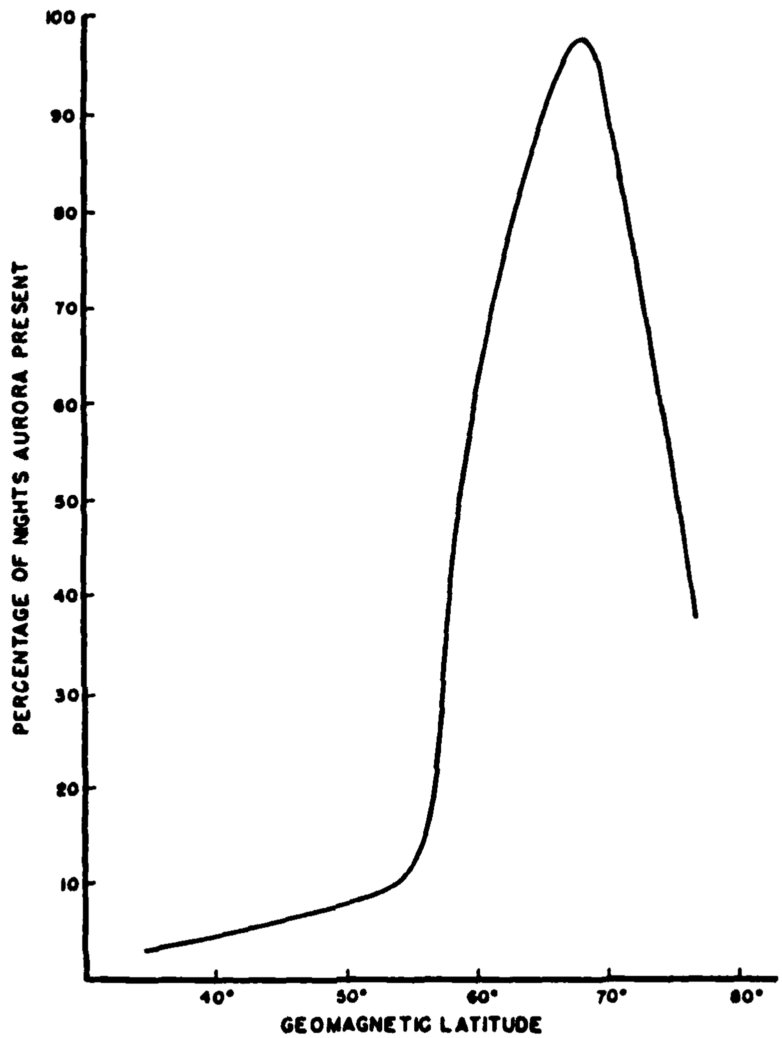


Figure 7 Variation in the frequency of the Aurora with geomagnetic latitude (from Petrie, 1963). This graph indicates that there is a 100% frequency of aurorae at about 68 deg gm latitude.

been seen much further south; on 4 February 1872, a display was seen in Bombay, India and throughout Egypt (McCormac, 1967). The third part of the auroral region is the auroral cap; it is found at geomagnetic latitudes above the auroral zone where the frequency of displays decreases. Like NLC, aurorae are most frequently observed near midnight. But unlike NLC/PMC, aurorae can be observed in seasons other than summer; they are in fact most often observed near equinoxes.

3.2 Possible Modes of Interaction Between Aurora and NLC/PMC

D'Angelo and Ungstrup (1976) found an anticorrelation between NLC occurrences and the daily sum of the magnetic K_p index for N. America. They suggested that this anticorrelation might be due to local heating of the atmosphere from electric fields in the ionosphere. Gadsden (1984) also suggested that there is a connection between the occurrence frequency of NLC and solar activity; the connection is that as solar activity increases, the upper atmospheric temperatures rise above the extremely low temperature required for NLC formation.

3.2.1 Direct Heating of the Mesopause

The main sources of heat input into the mesopause are local absorption of solar EUV and UV radiation, Joule dissipation of ionospheric currents (high latitudes only), energetic particle precipitation and dissipation of wave and turbulent energy (Forbes, 1983). Solar radiation is not associated with aurorae and will not be discussed. Dissipation of waves and turbulent energy will be discussed in the next section; this section will discuss energetic particles.

The auroral oval is a region of intense auroral particle precipitation; this phenomenon acts as a neutral atmospheric heat source with the heat mainly provided by ionic recombination. Cole (1962) noted that another important source of atmospheric heating comes from Joule dissipation of electric fields, which exist in the vicinity of the auroral oval and within the polar cap. Joule heating arises from the dissipation of electric fields which are generated by geomagnetic disturbances in the ionosphere. These electric fields accelerate ions; the ions will then acquire a drift velocity relative to each other and to neutrals. Collisions between species limit the drift velocities and convert some of the drift energy into heat (Rees and Walker, 1968). Ion-neutral collisions tend to transfer energy from ions of higher temperature to neutrals of lower temperature, acting as a heat source for the neutral gas. The temperature of the electron gas may also be greater than that of the neutral gas, and electron-neutral collisions will be another heat source for the neutral gas.

The interaction of the solar wind and the earth's magnetic field may overload the magnetotail with energy, creating the magnetospheric substorm (Hones, 1986). The substorm's lifetime is, roughly, one hour. This distinguishes it from a geomagnetic storm which has a lifetime of about 24 hours or more and is caused by solar flare activity (Mitchell, personal communication, 1985). A substorm is a way in which the magnetosphere sporadically releases energy which has been stored in the magnetotail; some of this energy helps produce aurora. The rate at which energy is deposited in the upper atmosphere during these polar substorms and geomagnetic storms can be large. Energy deposition associated with energetic particle precipitation (EPP) from an active aurora can exceed the solar EUV flux by a factor of 100 in a small area for a short time (Hays et al., 1972). Belon et al. (1969) found a total energy deposition for a 30kR arc of 380 ergs cm^{-2} s^{-1} (= 0.38 Wm^{-2}). Auroral electric fields have been observed to have magnitudes as great as 160 mVm^{-1}, but usually average 20-70 mVm^{-1} in intense magnetic storms (Hays et al., 1972). Joule heating resulting from fields this size can approach 100 ergs cm^{-2} s^{-1} (Banks, 1977). This heating rate may appear small compared to EPP, but EPP is of much shorter duration and covers a smaller area; thus, the major heat source during a polar substorm is via Joule heating associated with the auroral electrojet (Cole, 1962). Banks (1977) and others, however, have found that the average enregy deposited locally into the neutral atmosphere by EPP and Joule heating is roughly comparable in magnitude (about 100 ergs cm^{-2} s^{-1}), but both are still larger than the EUV input. He reports that Joule heating peaks at about 130 km while EPP peaks at about 100 km.

NLC/PMC are sensitive to the temperature of their environment. The ice nuclei at mesopause heights which serve as centers upon which ice crystals form directly from the vapor phase are called sublimation nuclei. Ice can form by sublimation if the air is supersaturated with respect to ice. It has already been shown how supersaturation can frequently occur at summertime high latitudes, and we know that a low (roughly 135K) mesopause temperature is a necessary condition for NLC formation. If EPP and Joule heating occurring at mesopause heights are large enough to significantly raise the local temperature, NLC/PMC generation may be prevented or retarded. How warm the mesopause must be to prevent cloud formation is uncertain; rocket temperature measurements in Alaska indicated a temperature of 135K in the presence of NLC and 165K with no NLC (Fogle and Haurwitz, 1966). But temperature measurements of this type do not exist in sufficient quantity to make a statistical analysis. The cumulative effect of aurorally induced heating mechanisms could be enough to dramatically raise the local temperature at about 85 km, thereby influencing cloud generation at that locale.

3.2.2 Wave Activity

NLC often exhibit wave-like structure. It has been theorized that atmospheric gravity waves may produce this effect in the clouds. Actual sources of these waves have not been accurately determined since the waves are seldom documented with enough detail to even warrant a preliminary study.

Most gravity waves are believed to originate in the troposphere, with typical sources being flow over irregular topography, jet streams, fronts or baroclinic instability. These waves propagate vertically, increase in amplitude with height at an exponential rate, and eventually reach convectively unstable amplitudes at mesopause heights where they "break" (dissipate). The dissipation generates turbulence which mixes the region, thus depositing momentum and raising temperatures near the mesopause. This may act as a deterrent to NLC/PMC formation since it could raise the mesopause temperature to a point which might preclude NLC/PMC genesis. However, the question here is whether or not auroral activity can produce gravity waves near the mesosopause which would have a retarding effect on NLC/PMC generation. An auroral origin of gravity waves is often claimed, but the mechanisms of their generation are not fully understood. It has been suggested that sudden aurorally induced heating may generate these waves. Testud (1970) made some numerical computations which show that heating can create gravity waves with characteristics of waves observed at mid latitudes. Hence, these aurorally induced gravity waves may transport the energy that is deposited at high latitudes to the lower latitudes during magnetic substorms. This may cause the excessive heating observed by satellites during auroral activity (see Jacchia and Slowey, 1964). Also, these laterally propagating gravity waves gradually dissipate as they move out of the auroral zone leaving momentum and induced temperature oscillations behind. It is known (USSA 1966 for example) that temperatures rise rapidly above and below the cold mesopause. The gravity wave induced temperature oscillations may exchange air of higher temperature with air of lower temperature, possibly creating non-ideal areas for cloud formation by raising the temperature to well above 135K. Thus, aurorally induced gravity waves may affect NLC/PMC in several ways.

Chrzanowski et al. (1961) observed infrasonic waves from the ground during periods of high geomagnetic activity. Maeda and Watanabe (1964) suggested that a possible source mechanism for these long period pressure waves is periodic heating by auroral particle precipitation and Joule dissipation around the 100 km level during pulsating aurorae. Perhaps as these waves propagate through and/or near the mesopause region, they upset the delicate thermodynamic balance needed for NLC/PMC formation thereby retarding cloud growth.

But to thoroughly understand the role of waves near the mesopause, a reliable knowledge of temperature and wind in the vicinity of these clouds is necessary. Unfortunately, this knowledge is limited.

3.2.3 Dynamics

Heating via EPP or Joule dissipation of electric fields in the auroral oval can affect the upper mesospheric and thermospheric wind patterns. With no auroral heating, a wind at this altitude region would flow across the polar cap from the dayside to the nightside due to solar heating. But aurorally induced heating in the oval can cause the upper mesosphere and thermosphere to expand on the dayside. This expansion can retard the wind pattern to some extent, depending on the intensity of the auroral heating. On the nightside, auroral heating helps produce the midnight surge; this phenomenon occurs during geomagnetic storms and is associated with strong equatorward winds around midnight (Schunk, 1983). Theon et al. (1969) found a relation between winds at the mesopause and the occurrence of NLC. Their study shows, to a 0.95 confidence level, that NLC are associated with lower wind speeds than those which occur on nights when there are no clouds. Perhaps the stronger winds formed in the upper mesosphere and thermosphere caused by heating during auroral events helps dissipate NLC/PMC by transporting ions and condensation nuclei needed for formation out of the immediate area. On the other hand, transport of ions into the region may cause too many sublimation nuclei, thus causing the NLC to become subvisual since there would be too many particles and each too small to see.

3.2.4 Composition

It is known that energetic charged particles entering the earth's atmosphere follow helical orbits along field lines until a collision occurs with an ambient atmospheric constituent, sometimes producing visible aurorae. There are three distinct cases of energetic particle precipitation which deposit energy into the middle atmosphere: galactic cosmic radiation (GCR), energetic solar proton events (SPE), and relativistic electron precipitation (REP) from the earth's radiation belts. Only SPE and REP affect the chemical composition of the middle atmosphere enough to possibly affect NLC/PMC formation.

Energetic protons (10-10^2 MeV) emanate from the sun following a solar flare and enter the atmosphere directly at the polar cap; the most energetic protons can penetrate equatorward to 60° gm latitude. Thus, changes caused by SPE are confined to regions above about 60° gm latitude. These solar proton events are a large ionization source in the mesosphere and upper stratosphere. They perturb the normal chemistry of the atmosphere and can lead to an enhancement of NO which in turn leads to a catalytic removal of O_3 (Thorne, 1980). It has been observed that SPE lead to a decrease of the mesospheric O_3 concentration by up to a factor of four (Weeks et al., 1972). Heath et al. (1977) reported a large ozone decrease around 45 km in the ozone profiles from Nimbus 4 backscattered ultraviolet data following the August 1972 SPE. Thomas et al. (1983) found a large reduction in mesospheric ozone (50-80 km) during the 13 July 1982 SPE, observed from both the infrared spectrometer and the ultraviolet spectrometer on the SME satellite. Recently, McPeters and Jackman (1985) analyzed ozone data from the solar backscattered ultraviolet instrument on Nimbus 7 from 1979 to the present. They have found five distinct cases in which ozone depletion is associated with SPE. Jackman and McPeters (1985) reported that most of this ozone depletion between 45-55 km was not caused by direct particle precipitation effects but by large ozone decreases at higher latitudes allowing increased penetration of UV to lower than normal altitudes. The lack of ozone depletion below about 60° gm latitude is evidence that the O_3 depletion is in fact related to this proton flux (McPeters and Jackman, 1985). They went on to suggest that HO_x reactions were responsible for the observed depletion.

According to Thorne (1980), REP events are sporadic and occur between 60-70° gm latitude. These intense events can have electrons penetrating down to about 50 km, producing X-rays (Bremstrahlung) which may penetrate into the stratosphere. It is believed that decreases in the mesospheric O_3 concentration can be expected during these events because of an enhanced OH production ($H + O_3 \rightarrow OH + O_2$). If REP and SPE can reduce the O_3 concentration, then one can reason that the upwelling of air within the high latitudes of the summer hemisphere middle atmosphere will decrease in intensity, since this circulation is driven by in situ solar heating, caused by UV absorption in the ozone layer. With decreased vertical transport, insufficient H_2O_v may reach mesopause heights to continue the NLC/PMC formation process; also this decreased updraft would decrease the strong adiabatic cooling with reduced O_3 to drive the circulation. In this case, the mesopause would not be as cold as is necessary for NLC formation. Bevilacqua (1978) cited that a 10K increase in the environmental temperature would require an increase in the water vapor mass mixing ratio by a factor of ten for ice particle persistence. If the ozone concentration were reduced, the vertical transport of water vapor would be reduced and the mesopause temperature would be increased. From Bevilacqua's conclusions, ice particle existence regions would be severely reduced or eliminated under these conditions.

3.2.5 Cluster Ions

Mass spectrometer measurements, like those done by Narcisi and Bailey (1965), have shown that the dominant lower E-region ions (O_2^+ and NO^+) continue to dominate the positive ion composition down to about 85 km (see Table 3.1). Below this altitude, water cluster ions of the form $H^+(H_2O)_n$ dominate (Johannessen and Krankowski, 1972). Electron attachment also becomes important, producing O_2^- as the primary negative ion, below about 80 km. The altitude where NO^+ and O_2^+ ions equal the density of water cluster ions is referred to as the transition height and is located at or near the mesopause. Johannessen and Krankowski (1972) find that the order of hydration, of cluster ions, increases with height up to the mesopause, where a rapid cutoff occurs. Simultaneous with this cutoff, they observed first Mg^+, Fe^+ to appear and then, at the higher levels, they observed the emergence of NO^+, O_2^+ as the dominant species. Identifying possible D-region ion paths that change the O_2^+ and NO^+ ions into the observed water cluster

Table 3.1 Positive ions in the lower ionosphere (from Johannessen and Krankowsky, 1972).

Altitude	Main Ion	Minor ion	Negative Charge
Above the transition height	NO^+, O_2^+	Si^+, N_2^+ Mg^+, Fe^+, Al^+, Na^+	Electrons
At the transition height	NO^+, O_2^+ $H^+(H_2O)_{2-3}$	$H^+(H_2O)$ $NO^+(H_2O)$, $NO^+(CO_2)$ $Na^+(H_2O)$, FeO^+	Electrons Negative ions Negatively charged aerosols
Below the transition height	$H^+(H_2O)_{2-6}$	O_2^+, NO^+ $NO^+(H_2O)_{1-2}$ $O_2^+(H_2O)$, O_4^+ $H^+(H_2O)$ H_3O^+OH $H^+(H_2O)_{1,2}(CO_2)$	Negative ions Electrons Negatively charged aerosols

ions had previously been difficult; it has now been done, although there are still some problems. Under quiet conditions, NO^+ (produced by solar Lyman-alpha radiation) is the dominant primary ion and clustering will follow its pathway. Under disturbed conditions, O_2^+ (produced by EUV on $O_2(^1\Delta g)$) dominates and clustering follows its pathway. This increase of O_2^+ during precipitation events may modify the ultimate composition of cluster ions throughout the D-region. The current state of understanding of water cluster ion processes is summarized in Figure 8.

The conversion of O_2^+ ions into water cluster ions has been explained by Feshenfeld and Ferguson (1969). Tracing the O_2^+ pathway, we find: $O_2^+ + H_2O + M \rightarrow O_2^+(H_2O) + M$. But this reaction does not occur in the D-region because it is too slow, due to the low water vapor concentration at these altitudes because it involves a three-body collision. An accepted way in which O_2^+ may be converted into a water cluster ion is through the following chain of reactions:

$$O_2^+ + O_2 + M \rightarrow O_4^+ + M$$

$$O_4^+ + H_2O \rightarrow O_2^+(H_2O) + O_2$$

$$O_2^+(H_2O) + H_2O \rightarrow H^+(H_2O)(OH) + O_2,\ n > 2$$

$$H^+(H_2O)OH + H_2O \rightarrow H^+(H_2O)_2 + OH$$

$$H^+(H_2O)_n + H_2O + M \rightarrow H^+(H_2O)_{n+1} + M$$

The final reaction listed above is temperature dependent - the colder the environment, the larger the cluster ions. With a low summer

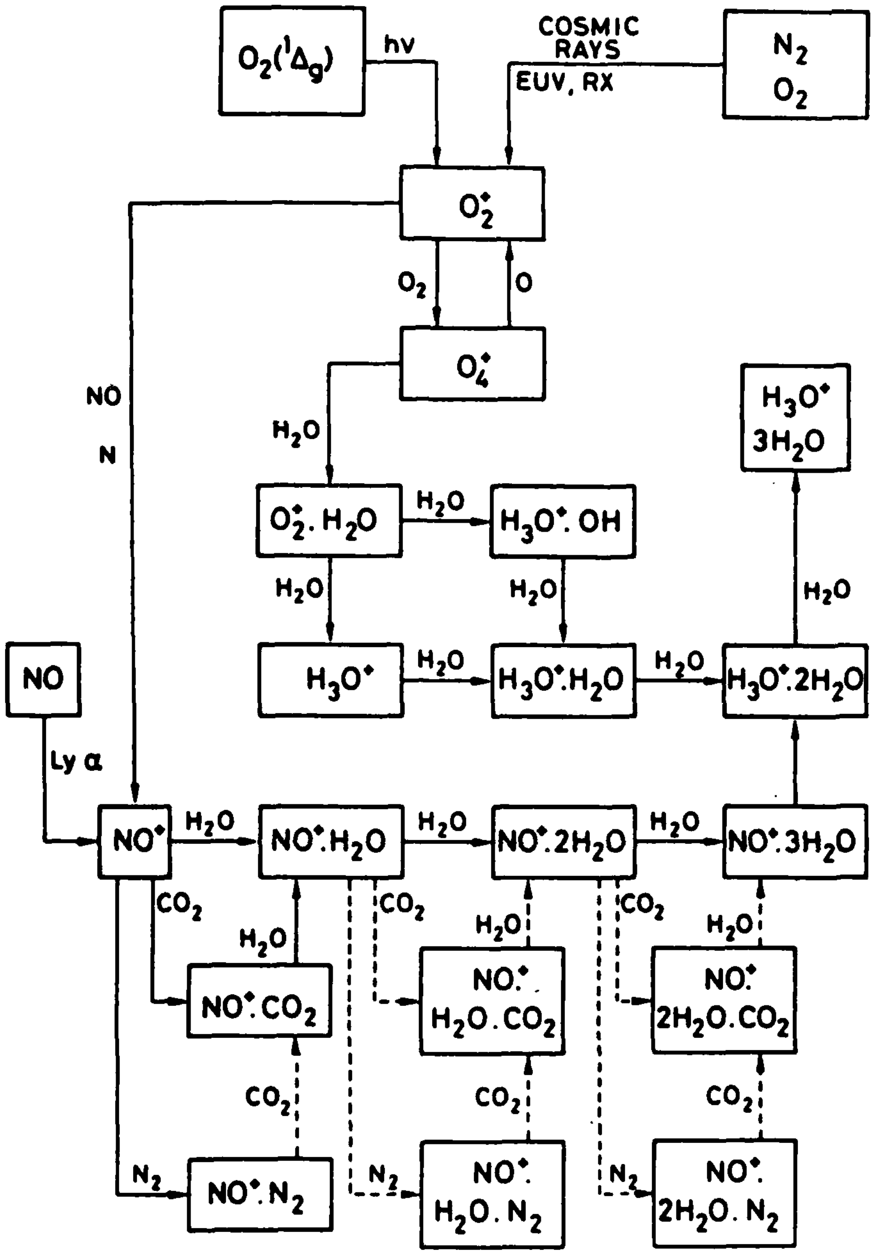


Figure 8 Schematic diagram of D region positive ion chemistry (from Brasseur and Solomon, 1984).

mesopause temperature of 120K, thermal breakup is negligible and, thus, the largest clusters occur near the high latitude summer mesopause (Reid, 1976). But one must remember that the O_2^+ pathway to cluster ion formation is followed during disturbed conditions where the electron density is increasing in the upper D-region. The increased ionization, which accompanies disturbed conditions, decreases the recombination lifetimes of electrons, and hence molecular ions will have a greater tendency to recombine before they form clusters. This will lower the transition region to approximately 70-75 km when ionization is high, rather than the usual 80-85 km during undisturbed conditions. The temperature at 70-75 km may be 30K higher than that at 80-85 km. This increase in temperature, due to a lowering of the water cluster formation altitude, may inhibit cloud formation during geomagnetically disturbed conditions.

The conversion of NO^+ ions into water cluster ions is a more complex problem than the O_2^+ conversion. Generally, the NO^+ reaction scheme is:

$$NO^+ + H_2O + M \rightarrow NO^+(H_2O) + M$$

But this reaction is not fast enough and the ions are lost through recombination. Thus, additional three-body schemes are needed involving more plentiful neutral constituents. Because of low pressures and low water vapor concentrations in the D-region, one must consider a scheme of reactions of the form:

$$NO^+ \cdot nH_2O + X + M \rightarrow NO^+ \cdot nH_2O \cdot X + M$$

$$n = 0,1,2,3 \text{ and } X = N_2, CO_2$$

After some manipulating with switching reactions of the form:

$$NO^+ \cdot nH_2O \cdot N_2 + CO_2 \rightarrow NO^+ \cdot nH_2O \cdot CO_2 + N_2$$

$$NO^+ \cdot nH_2O \cdot CO_2 + H_2O \rightarrow NO^+ \cdot (n + 1)H_2O + CO_2$$

one gets (for example):

$$NO^+(H_2O)_3 + H_2O \rightarrow H^+(H_2O)_3 + HNO_2$$

Hence, this NO^+ sequence also offers an explanation for the formation of water cluster ions near 80 km.

According to Mitchell (personal communication, 1985) when the temperature is greater than 215K, the collisional decomposition of NO^+N_2 is larger than the switching reaction with CO_2. This would decrease the production of water cluster ions and thus decrease the chance of NLC formation at such temperatures. This agrees with Fogle and Haurwitz' statement that NLC formation occurs at low mesopause temperatures, of about 135K. If water clusters do enhance NLC/PMC, they would generally follow the NO^+ pathway in low temperature regions; the O_2^+ pathway (followed under disturbed conditions) involves cluster formation at lower heights where it is probably too warm for NLC/PMC genesis.

3.3 Effects of Geomagnetic Activity on NLC Over W. Europe

The K_p index is a planetary index designed to measure solar particle radiation by its magnetic effects. It is a good indicator of auroral activity on a global scale. The daily sum of the magnetic K_p index (ΣK_p) for June, July and August of 1981 and 1983 was compared to NLC data from W. Europe for the same time period (see McIntosh and Hallissey, 1982 or Gavine, 1984 for the NLC data). After plotting all NLC occurrences reported in each summer month versus ΣK_p and statistically analyzing the results, no correlation (or anticorrelation) was found. NLC were seen to occur during highly disturbed conditions ($\Sigma K_p > 30$), quiet conditions ($\Sigma K_p < 10$) and values in-between these extremes (see Figures 9a-f). This differs from the results of D'Angelo and Ungstrup (1976); they found an anticorrelation between NLC occurrences and the ΣK_p using N. American data. The reason for the differnce between the present work and theirs is probably because the auroral zone is far north of W. Europe, yet lies in the center of Canada. Since the auroral zone is further poleward in W. Europe, the five modes of interaction listed in Section 3.2 should be ineffective at dissipating NLC there. In the N. American case, with the auroral zone reaching its point nearest to the equator, the modes of interaction listed in Section 3.2 may have an effect on NLC formation (see Figure 10). Therefore, I suggest that due to auroral zone asymmetry about the globe, there should be little anticorrelation of NLC with ΣK_p in W. Europe.

Obviously, an analysis such as the one above is very subjective. Aurorae and NLC cannot be seen all the time because of tropospheric clouds; this might alter the graphs in Figures 9a-f somewhat. Also, there is no irrefutable evidence linking the presence of aurora to the distribution to NLC/PMC; only suggestions to this effect exist, such as those listed in Section 3.2. Perhaps small scale auroral events do inhibit cloud formation while large proton aurorae enhance NLC/PMC by

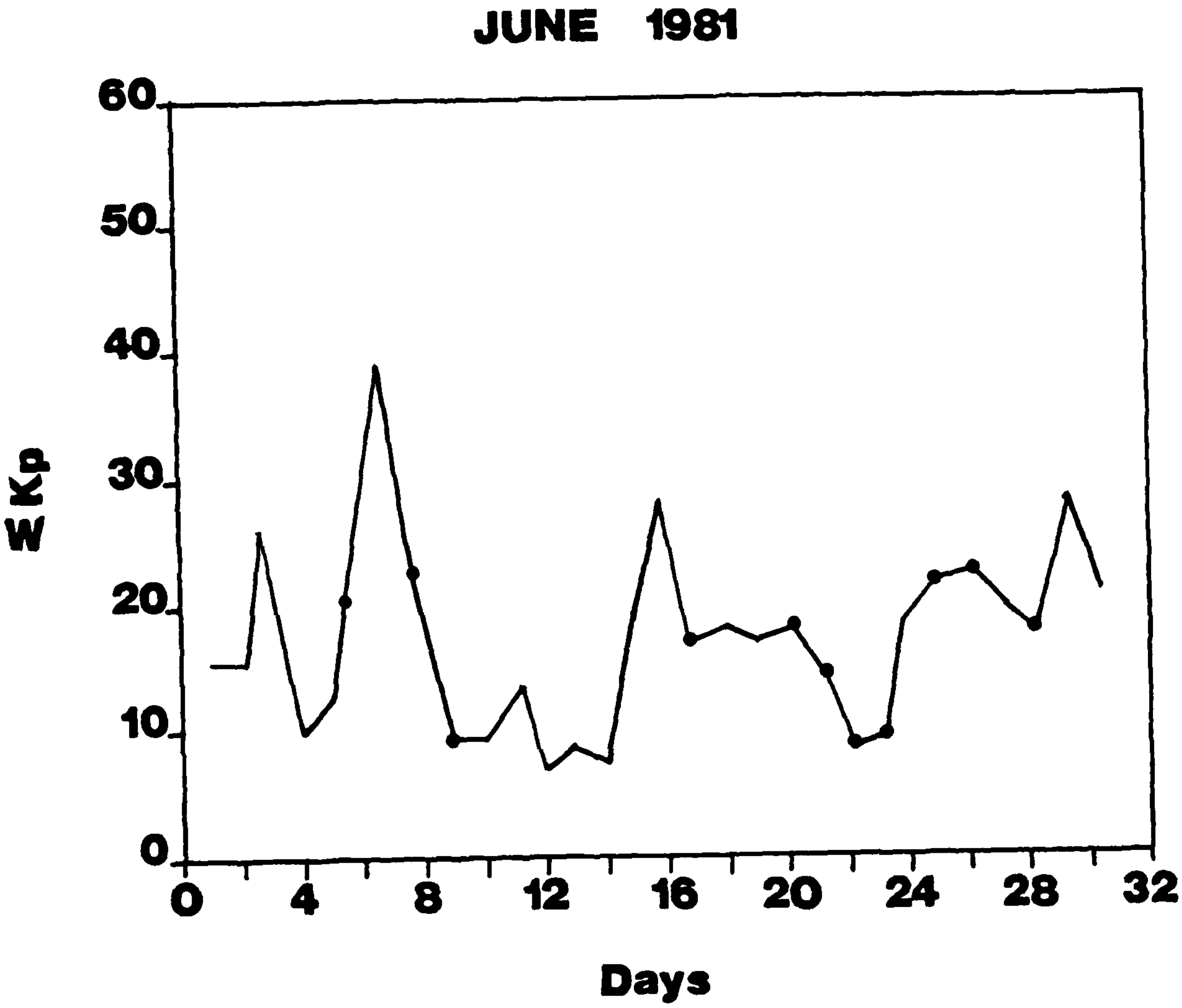


Figure 9a ΣK_p and NLC occurrence over West Europe during June, 1981. Solid line is fluctuation of ΣK_p values during the month while large dots mark NLC sightings as reported in Meteorology Magazine. There is little correlation or anticorrelation; NLC were sighted when ΣK_p had large values, small values and values in between. Figures 9b-f (on following pages) show similar results.

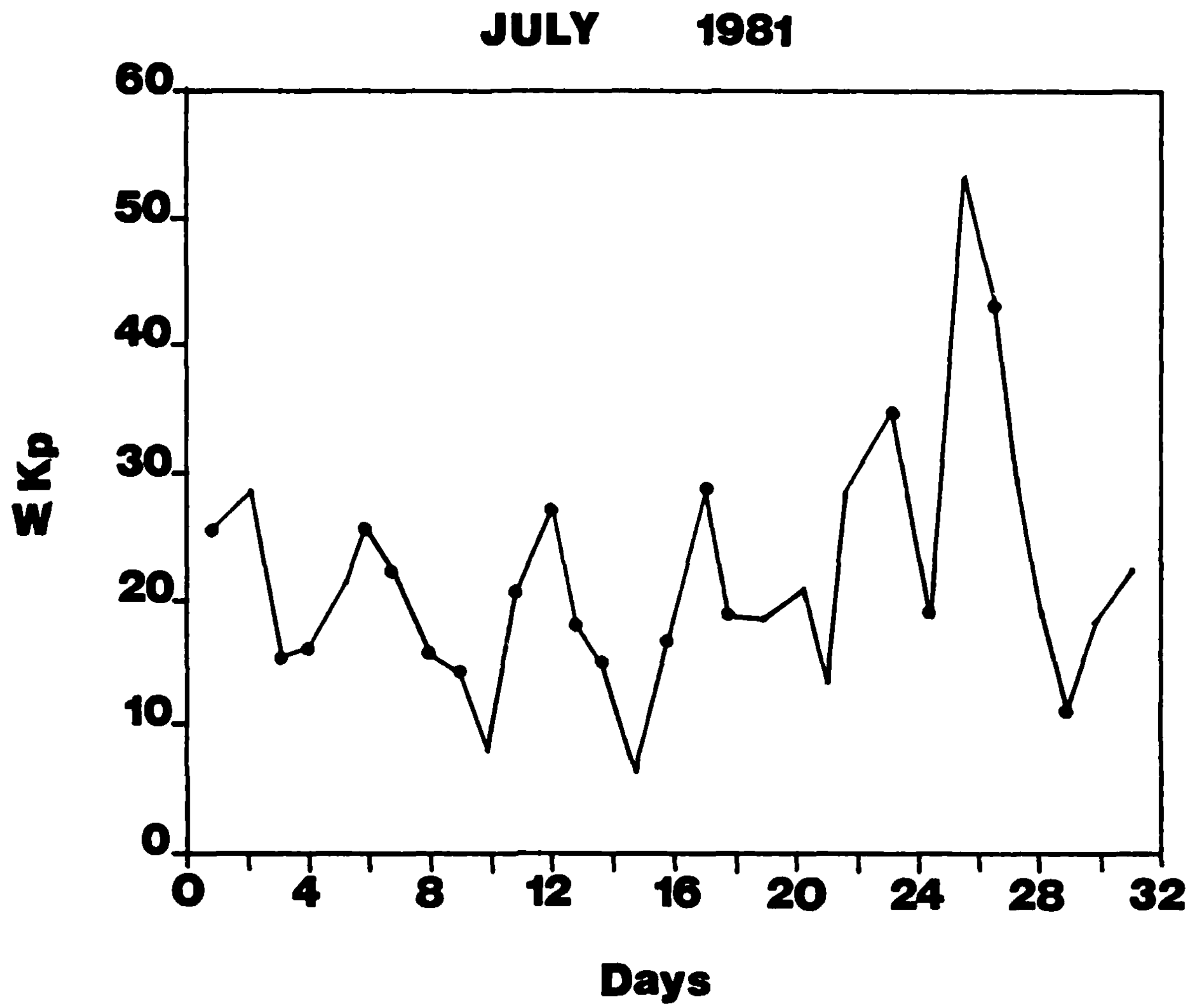


Figure 9b

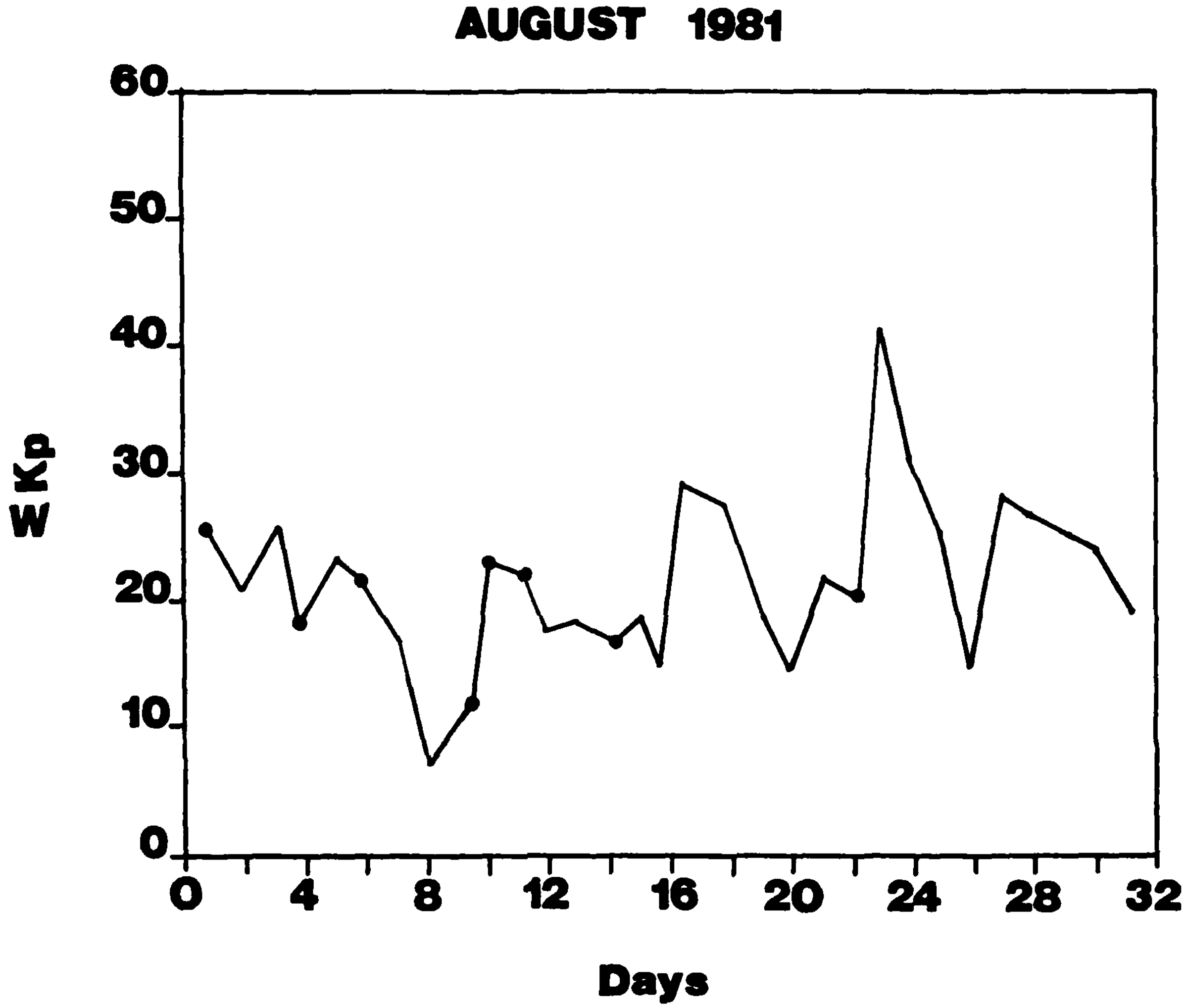


Figure 9c

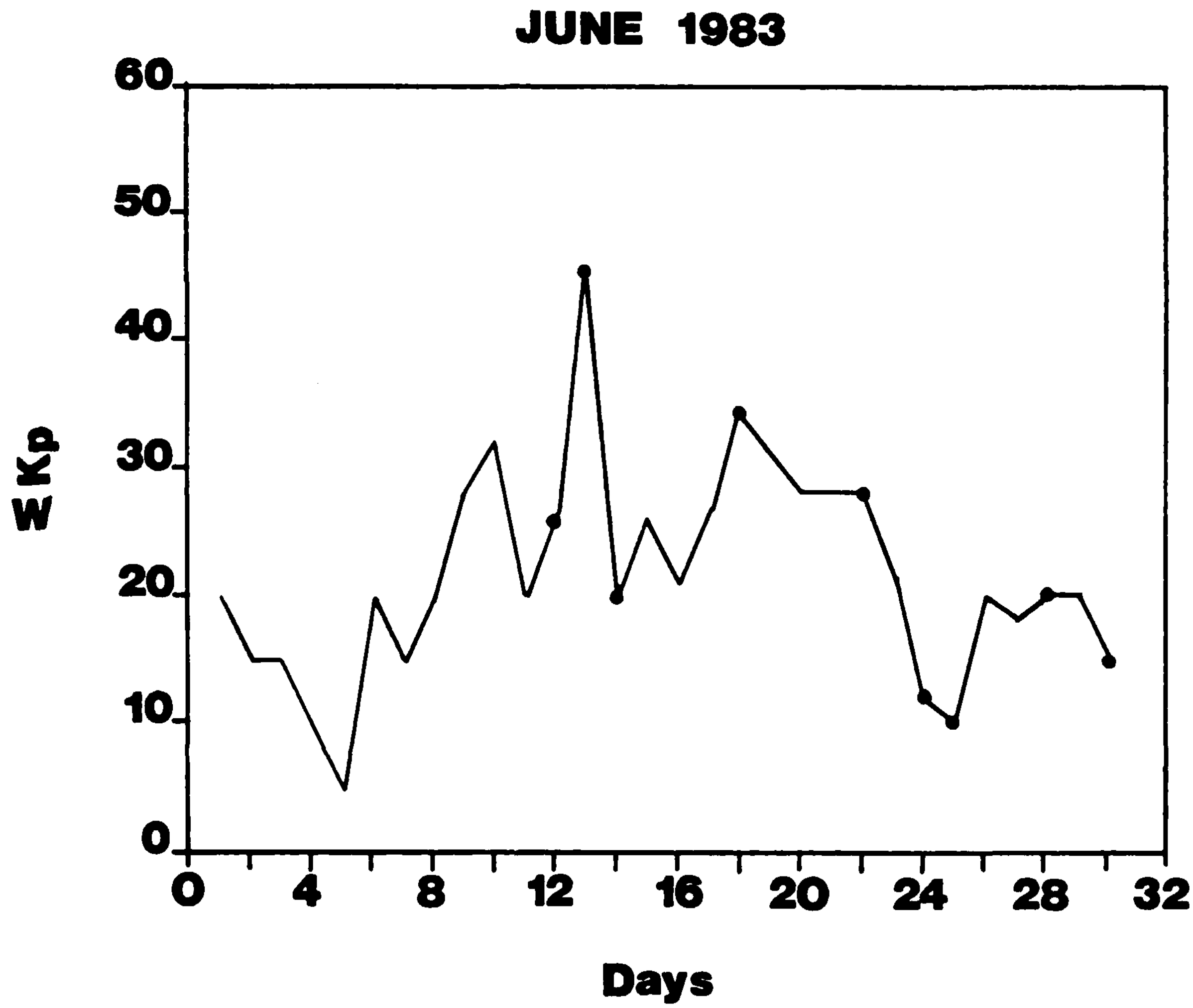


Figure 9d

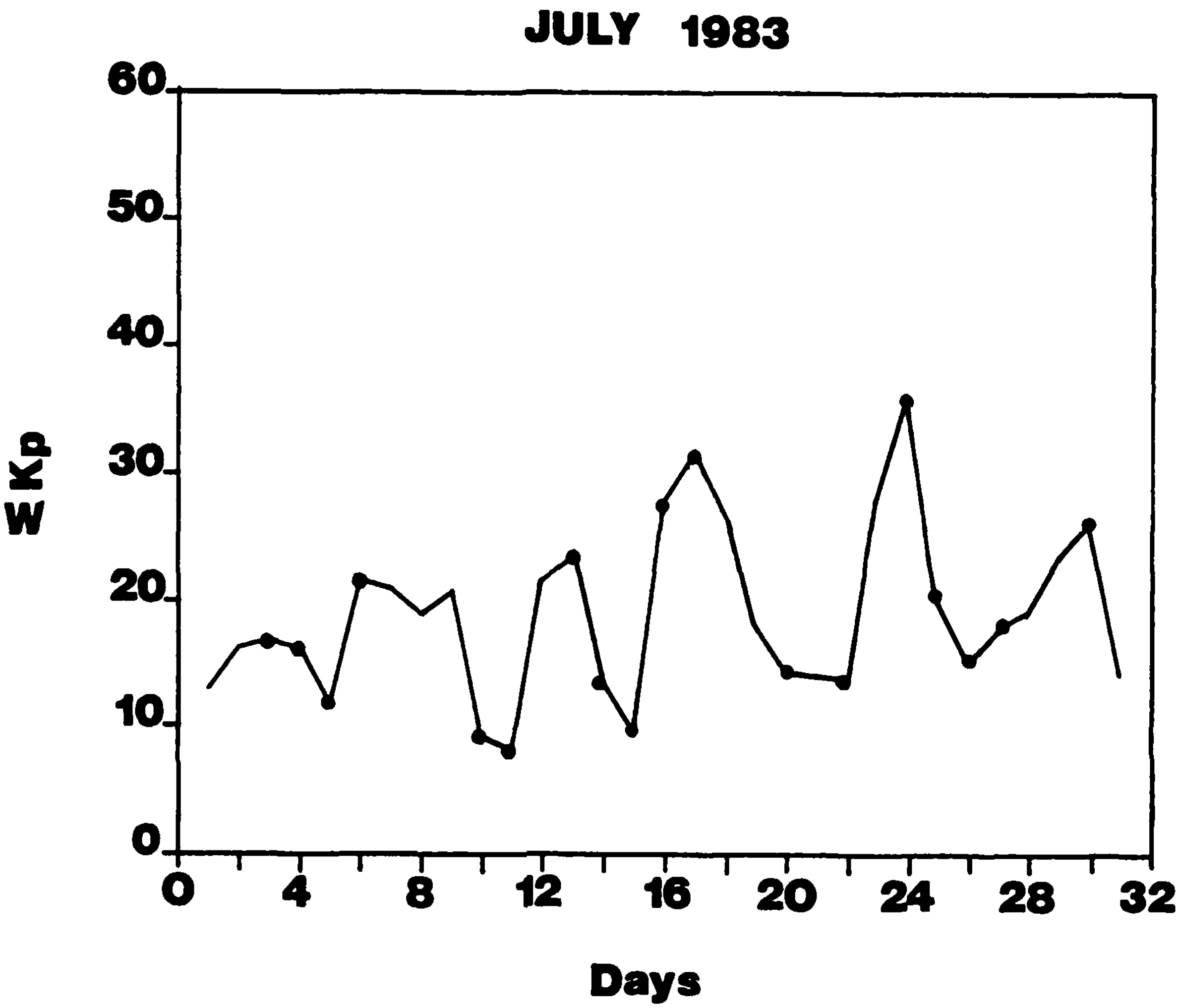


Figure 9e

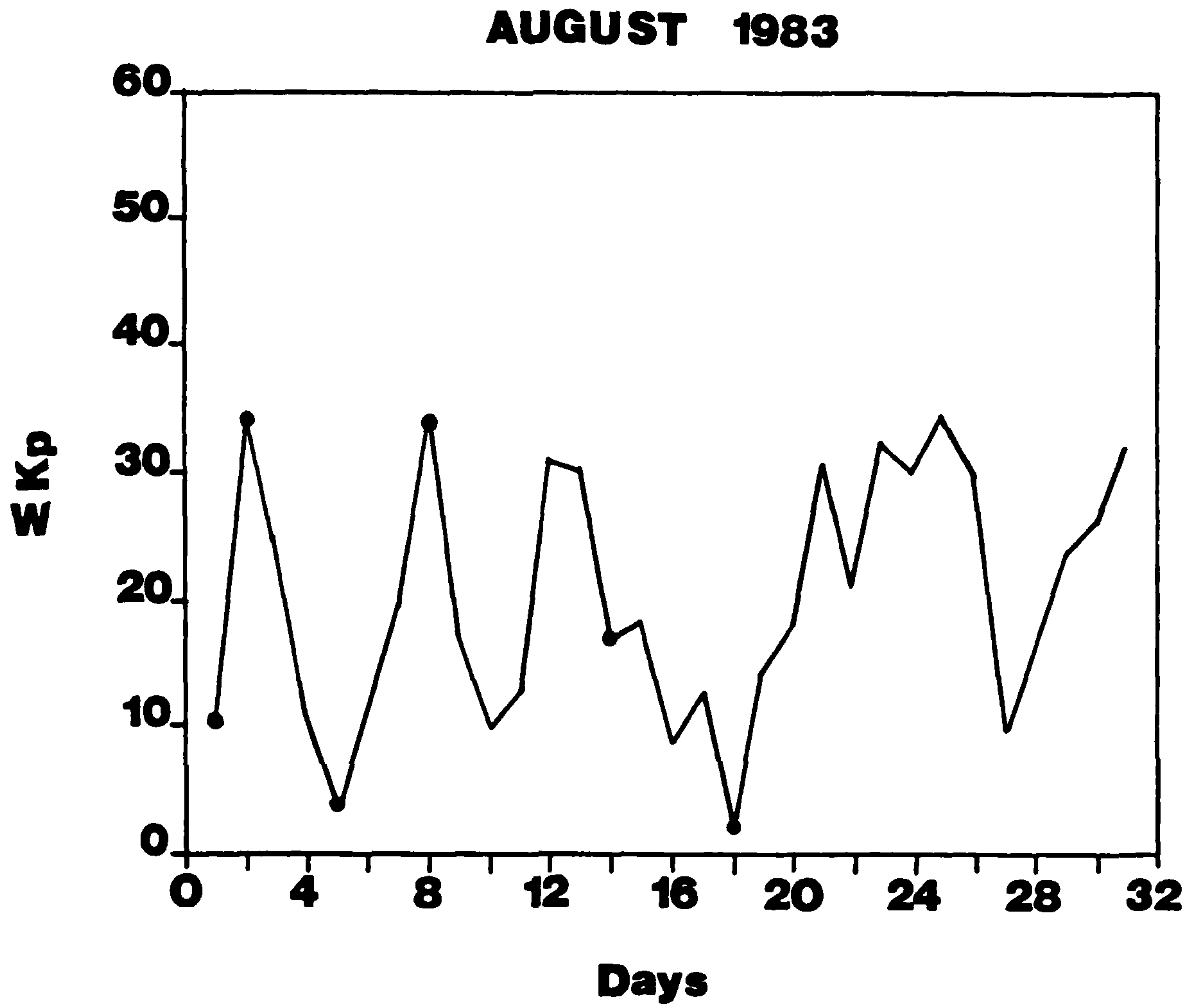


Figure 9f

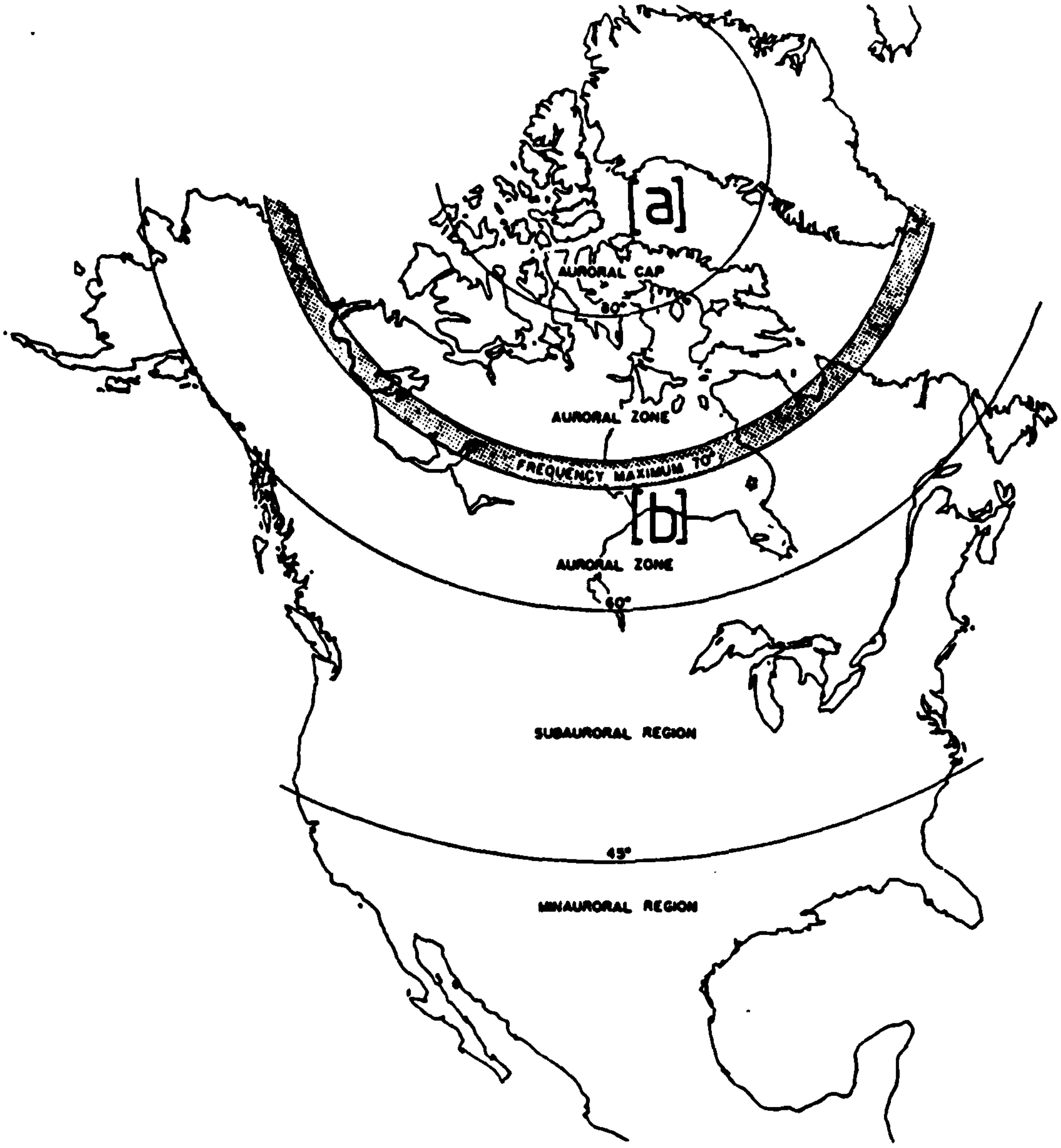


Figure 10 Auroral Zone over North America and NLC frequency (adapted from Petrie, 1963). Zone [a] denotes a PMC region (a "ubiquitous" scattering layer). Zone [b] denotes an NLC region (a "sporadic manifestation" of PMC to lower latitudes).

first destroying the cloud (environmental heating) then mixing and adding additional protons to the NLC/PMC environment which could be the source of new water cluster ions upon which new ice crystals form.

Knowing the time scales at work in all the phenomena discussed above is necessary in order to better understand possible NLC/PMC production and destruction processes. When an aurora occurs, environmental heating is nearly immediate. Hence, we shall assume that the time scale of aurorally induced heating is on the order of seconds to minutes. And since heating is believed to be detrimental to NLC/PMC formation, we shall also assume that the NLC/PMC destruction time scale is on the order of seconds to minutes. But aurora also mix and add additional protons to the environment, thereby possibly leading to an enhancement of NLC/PMC production. The time scale of mixing (and therefore NLC/PMC production) is difficlt to estimate, but is probably at least one order of magnitude greater than that of heating and destruction. Thus, we shall assume the time scale of mixing and production is on the order of hours. This agrees with the findings of Turco et al. (1982) who reported that the formation of NLC particles requires a time scale on the order of about 12-24 hours. Now one realizes the necessity (and complexity) of understanding time scales. An immediate effect of auroral activity could be to destroy NLC/PMC via heating; yet if one considers a longer time scale, aurorae may actually enhance NLC/PMC production by mixing and adding more protons to the environment.

The random variation of NLC occurrences with ΣK_p, as seen in Figures 9a-f, may be due to the space scales one uses for analysis.

For example, K_p is a planetary index designed to measure solar particle radiation by its magnetic effects; NLC on the other hand are mesoscale phenomena occupying small volumes of the atmosphere at high latitudes. Thus, trying to draw conclusions about mesoscale phenomena while examining them with a global index could lead to a correlation, an anticorrelation or a random variation between the two. A way around this scale problem would be to plot ΣK_p data for a single station versus NLC occurrences for that same area, thereby making ΣK_p data mesoscale. This data was, unfortunately, unavailable for this research.

3.4 Effects of Solar Proton Events on NLC Over W. Europe

McPeters and Jackman (1985) found five distinct recent cases in which ozone destruction is associated with SPE (see Section 3.2.4). The dates for the cases are 7 June 1979, 21 August 1979, 13-14 October 1981, 13 July 1982 and 8 December 1982. According to Jackman and McPeters (1985) ozone depletions associated with SPE have been observed four other times as well: November 1969, January and September 1971 and 4-8 August 1972 (the largest event). This study is only concerned with cases which could interact with NLC, i.e., (roughly) summertime SPE; thus, we shall consider 7 June 1979, 21 August 1979, 4-8 August 1972 and 13 July 1982. In this study, these cases were compared with NLC data from W. Europe (as reported in Meteorology Magazine). The 13 July 1982 case then had to be omitted from the analysis since there was no NLC data available from Meteorology Mazagine for that date.

The findings were intriguing, yet there is obviously not enough data to make definite conclusions. What was found, for the three cases, was that SPE seem to be anticorrelated with NLC occurrence over W. Europe. On 7 June 1979, an SPE was observed; no NLC were observed over W. Europe on this date or 8-9 June. Not until 10 June were NLC reported again (NLC had been reported earlier in June). For the SPE of 21 August 1979, no NLC were reported on that date or 22-24 August. Not until 25 August were NLC reported again. And during the extremely intense SPE of 4-8 August 1972, NLC (and intense aurorae) were observed on 4 August but no more NLC were observed for the remainder of August. Hence, Western European NLC (and even other regions of NLC) may be anticorrelated with SPE, especially intense events. The possible reason is that SPE can alter the atmospheric chemistry, thereby possibly influencing NLC formation.

4.0 DISCUSSION AND SUGGESTIONS FOR FURTHER STUDY

In this study, we have reviewed some general characteristics of polar mesospheric (noctilucent) clouds and aurorae and have discussed a number of ways in which aurorae may be coupled with NLC/PMC. Possible modes of interaction are:

(1) Direct heating of the mesopause by particle precipitation and Joule dissipation of electric fields. The cumulative effect of these two parameters may raise the mesopause temperature to one that is too high for supersaturation to occur. Result - a possible anticorrelation of auroral activity with NLC/PMC.

(2) Aurorally induced gravity waves may cause temperature fluctuations near the mesopause which could result in a rapid warming trend. Result - a mesopause temperature too high for NLC/PMC genesis and thus, a possible anticorrelation between auroral activity and NLC/PMC. Aurorally induced infrasonic waves may also effect the NLC/PMC environment, creating unfavorable growth conditions.

(3) Heating in the auroral oval affects wind patterns. NLC have been observed to be associated with low wind speed areas. Strong winds formed in the upper mesosphere and thermosphere caused by auroral heating may help dissipate NLC/PMC. Result - a possible anticorrelation between auroral activity and NLC/PMC.

(4) SPE and REP have been observed to reduce the ozone concentration. This reduction could, in succeeding days, decrease vertical transport, preventing water vapor from rising to mesopause heights and preventing the summer mesopause from becoming extremely cold. A rise

in temperature and a decrease in the water vapor concentration could reduce the chances of cloud formation. Result - a possible anticorrelation between auroral activity and NLC/PMC. But one must realize that this cannot be an immediate cause and effect. Let us assume that the mesospheric updraft is between 1-10 cm/s. The maximum water vapor mixing ratios in the middle atmosphere are found at about 60-65 km. Water vapor rising at 1 cm/s from this height to NLC/PMC heights will take about 25 days. Therefore, a reduction in ozone concentration would probably not affect the water vapor flux into the mesopause (and concomitant NLC/PMC formation) for several days. However, it is interesting to note that this travel time of 25 days is roughly the same length of time it takes for one solar revolution. Let us assume active sun conditions in which there is intense solar flare activity and a group of sunspots which persists for more than one solar revolution. The resulting high levels of geomagnetic activity (intense SPE for example) from this active sun could reduce the ozone concentration for a time period greater than the travel time of water vapor up into the mesopause via the mesospheric updraft. If so, NLC/PMC production could decrease due to a drop in the water vapor flux. Hence, ozone concentrations, the mesospheric updraft and the resulting water vapor flux at mesopause heights may all depend on the level of solar activity.

(5) The largest water cluster ions form near the high latitude summer mesopause by following either the NO^+ or O_2^+ pathway. The O_2^+ pathway is followed during disturbed conditions; when this occurs, the transition region from O_2^+ to water cluster ions is lowered to

about 70-75 km (recalling that during undisturbed conditions when the NO^+ pathway is followed, the transition height is about 80-85 km). The lower O_2^+ transition region will be in a region of the atmosphere that has a higher temperature which could inhibit cloud formation and result in the possible anticorrelation of aurorae and NLC/PMC. Hence, the NO^+ pathway to water cluster formation is probably more influential in enhancing NLC/PMC genesis than the O_2^+ pathway.

The above five statements are just ideas, none of which have been proven. The effects of geomagnetic activity and SPE on NLC over W. Europe were also examined in this paper. It was suggesetd that due to auroral zone asymmetry about the globe, with W. Europe being south of the maximum auroral frequency zone, NLC are not anticorrelated with the ΣK_p index (as was found to be the case over N. America). Also, with very limited data available, it was reported in this study that NLC may be anticorrelated with SPE.

As suggestions for future studies, it is recommended that the following be done:

(1) A simple statistical analysis which compares satellite and ground-based NLC/PMC data with satellite images of aurorae at the same place and time. This should unequivocally answer the question of aurorae and NLC/PMC correlations.

(2) Additional measurements of temperature, water vapor concentration, ozone concentration, winds and other questionable parameters at mesopause heights from 50-90°. Better temperature measurements at all northern latitudes is especially important if we are to understand the physics of the mesopause region; note that all five statements numbered above are directly related to temperature.

(3) Construction of a NLC/PMC cloud chamber strictly simulating high latitude, summer mesospheric conditions in order to determine such unknowns as cloud particle size, origin and composition. Answers to these questions could shed light on many other questions.

(4) Systematic temperature measurements in the NLC/PMC regions when aurorae and NLC/PMC are occurring simultaneously. If the temperature increase due to auroral heating is significant, changes in the clouds may result.

(5) Plotting ΣK_p data for a single station versus NLC occurrences for that same area. This would help determine if ΣK_p (mesoscale) is correlated, anticorrelated or randomly varies with NLC occurrences.

APPENDIX A

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