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The influence of planetary waves on noctilucent cloud occurrence over NW Europe.

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Abstract

Observations of noctilucent clouds (NLC) from North West Europe have been collected by a network of observers for almost 40 years. Previous analyses of the observations have found an apparent increasing frequency of occurrence, a 10-11 year modulation and evidence for 5-day periodicity. Here we re-examine the observational data for NLC occurrence to test whether the observed variations can be explained by planetary wave activity in the middle atmosphere. Planetary wave amplitudes and phases in the lower mesosphere are derived from global meteorological assimilations from 1979-2000 and extrapolated to the mesopause. When the NLC observations are selected from a constant observing area, we find that there is no substantial trend in yearly NLC occurrence over the observation period, whereas the 10-11 year and 5-day modulations remain significant. We find a strong correlation between the probability of observing NLC and the combined effects of stationary, 16-day and 5-day planetary waves at the NLC location. The most reasonable explanation for the correlation is that that probability of observing NLC depends on the strength of the wind from the north, which in turn depends on the amplitude and phase of the planetary waves. The influence of planetary waves on NLC occurrence may to a certain extent explain the 10-11 year periodicity in NLC. This possibility is a consequence of a strong correlation between the phase of the stationary planetary waves and the 10-11 year cycle of solar activity during the period 1979-2000.

Introduction

Noctilucent clouds (NLC) are very high-altitude (ca 80-85 km) clouds which can be seen after sunset at mid- to high latitudes during the summer months. They are thought to be composed of water-ice which freezes out of the atmosphere because of the extremely low temperatures which prevail at the high-latitude summer mesopause (for a review see *Gadsden* [1989]). They are thought to be closely related to the phenomenon of 'Polar Mesosphere Summer Echoes', the latter being strongly enhanced VHF radar echoes observed from about the same height region during the same season. PMSE are thought to be caused by very small, charged ice particles, whereas noctilucent clouds must comprise much larger particles to explain their reflectivity for visible light (for a review see *Cho and Röttger* [1997]). Climatological studies of PMSE with good height resolution have been possible for only the last few years, since the installation of suitable radar facilities at high latitudes. Up to now, the data records are not long enough to allow study of possible decadal or long-term trends in PMSE. However, the continuous observations available using VHF radar allow periodicities from a few minutes to a few days to be studied very effectively. In particular, 5-day periodicities have been found using the ESRAD VHF radar in Kiruna, Sweden (67 ° N, 20 ° E) and these have been related to 5-day planetary waves by *Kirkwood and Réchou* [1998] and *Kirkwood et al.* [2002]. Temperature peaks at 85-95 km, corresponding to peaks in 5-day waves found in global meteorological assimilations at ca. 60 km altitude, have been found to correspond to reduced occurrence of PMSE. Five-day PMSE periodicities in radar data from Alaska have also been found and proposed to be related to a 5-day cycle of ice formation and sublimation by *Sugiyama et al.* [1996]. 5-day periodicities in noctilucent clouds have also been reported by Sugiyama (unpublished manuscript, 1997) and *Gadsden* [1985]. So far, there seems to have been no systematic study of whether periodicities in noctilucent clouds might be due to the effects of planetary waves, even though substantial temperature oscillations (up to 10 K amplitude) have been observed near the summer high-latitude mesopause. For example, *Espy and Witt* [1996] and *Espy et al.* [1997] have reported direct observations of 16-day temperature oscillations at 60° N, 20°E and *Rosenlof and Thomas* [1990] inferred 5-day temperature oscillations over both summer polar regions from satellite ozone observations. *Espy and Witt* [1996] compared with noctilucent cloud observations for one season but found , surprisingly, that the NLC appeared at the warm parts of the 16-day waves. However, they had observations only for two 16-day cycles, so they were not able to draw any firm conclusions. This study attempts, therefore, a systematic investigation of whether planetary waves might provide an explanation for the day-to-day and year-to-year variability in noctilucent clouds using observations from as long a time interval as possible – in all 22 summer seasons.

Noctilucent Cloud Data

Observations of noctilucent clouds have been collected and reported by a network of amateur observers in NW Europe (primarily in Scotland) since 1964. These observations have been published by *Paton* [1965-1973], *McIntosh and Hallissey* [1974-1983] and *Gavine* [1984-1993, 1992, 2000], covering the period 1964 – 1997 We use these published observations plus, for the more recent years, the collected reports from approximately the same group of observers at the observers web site (http://www.kersland.u-net.com/nlc/nlchome.htm.). Note that comprehensive summaries and analyses of the same observations up to 1995 have previously been published by *Gadsden* [1998a] and in references therein.

For our purposes we use only observations made from Scotland, England, Ireland, Wales, Denmark, and the Netherlands, but not from Germany, Iceland, Sweden, Norway and Finland. We restrict the area since we want to study the influence of planetary waves which have strong spatial variations and because our data set should be as consistent as possible over the whole period of study. The number of observers making reports from the former group of countries has remained about the same while the numbers from the second group have fluctuated widely from year to year. Note that the NLC themselves are most often located at higher latitude than the observing sites. The mean latitude of the southernmost edge of the NLC observed from this region has been found by *Gadsden* [1998a] to lie close to 60 ° N, with almost all observations lying within 5° north or south of this latitude. The number of nights each year when NLC were reported is shown in Figure 1 (black bars in second panel). The whole data series from 1964-2000 is shown in the Figure although only the years 1979-2000 are used in this study for comparison with planetary wave activity. For comparison with planetary waves we must additionally restrict our analysis to the period during the summer when the easterly stratospheric wind is well established and the correct extraction of planetary waves from the meteorological data becomes possible (see below for more details). We keep the same period for every year – from the night between days 165/166 to the night between days 200/201 (14 June - 19 July - for non-leap years, 13 June – 18 July for leap years). The number of nights when NLC were reported each year, within this restricted time interval, is also shown in Figure 1 (white bars in second panel). The upper panel of Figure 1 shows the level of solar activity using the mean solar radio flux (at a wavelength of 10.7 cm) for the months June and July.

The year-to-year variations, in both the total number of NLC and the number within our restricted period day 165-201, show a cycle of about 10 years, i.e. a period close to the cycle of solar activity. *Gadsden* [1998a] has tested the cross-correlation between solar flux and the total number of nights with NLC from 1964-1995 and found that there is no significant difference in the periods (10.3 – 10.5 years) but that the minimum in NLC occurs 2 years after solar maximum. The cross-correlation for the whole period 1964-2000 is shown in Figure 2a. For the restricted period 1979-2000 and for our mid-summer period days 165-201 only, the cross-correlation is shown in Figure 2b. Confidence levels for the correlations have been found by making a large number of trials using random-order selections from the real NLC observations (nights per year). We see that, for the whole period 1964-2000, the correlation reaches the 99% confidence limit (i.e. only 1% of the randomised trials gave higher correlation). For the restricted interval 1979-2000 , days 165-201, the correlation reaches the 95% confidence limit. In all cases the correlation (in practice an anticorrelation) is best when the solar flux from the previous year, or the year 2 years earlier is correlated with the NLC observations. No physical explanation for this lagged correlation has so far been found although *Gadsden* [1998a] suggested that the well known solar-cycle modulation of the 30 hPa geopotential height might play a role (for a review of the latter see *van Loon and Labitzke*, [2000]).

As mentioned in the introduction, both *Gadsden* [1985] and *Sugiyama* [1997] have reported a 5-day periodicity in NLC, using whole seasons of observations prior to 1984 and 1992, respectively, and this forms part of the motivation for our search for a possible link to planetary waves. We do not repeat those authors detailed studies of the 5-day periodicity, but simply check that it is still present in our restricted interval 1979-2000, days 165-201. This is illustrated by Figure 3 which shows the interval between NLC displays which were reported as 'bright'. It can be seen that a 5-day interval is the most common.

It should be noted that the series of noctilucent cloud occurrence in the second panel of Figure 1 does not show any sign of the secular increase reported by *Gadsden* [1998a]. This is true both when considering the whole season and when considering only our restricted mid-summer period (days 165-201). Our source of observations up to 1995 is the same as in Gadsden's analysis, and we have found that this difference is due to the strict geographical restriction of the observation area for the data in Figure 1 (in particular the non-inclusion of observations from Finland).

Planetary Wave Analysis

To study the possible influence of planetary waves we use the global meteorological analyses from the UK Meteorological Office stratospheric assimilations. From 1979-1994 the TOVS analysis [*Bailey et al*., 1993] is used, from 1995-2000 the UKMO-UARS data set [*Swinbank and O'Neill*, 1994]. The former is available at 11 pressure levels from 850 hPa to 1 hPa (altitudes ca. 1 km – 50 km) and the latter for 22 pressure levels from 1000 hPa to 0.3 hPa (altitudes ca. 0 km – 60 km). One global array is available for 12 UT each day. To extract planetary waves we use the geopotential height fields. A Fourier transform is used to determine the complex amplitude of the wave number 1 component at each pressure level (altitude) and latitude for each day. The time series of complex amplitudes for each spatial grid point is then filtered (using a 5-pole bi-directional Butterworth filter) to extract 4 wave components with period 4-6 days, 6-12 days and 12-20 days and > 20 days. These we take to represent ’5-day’, ‘10-day’, ’16-day’ and 'stationary' waves, respectively. The time resolution of the meteorological data precludes useful analysis of shorter period waves, such as the ‘2-day’ waves which have been reported in winds at mesopause heights (see e.g. *Jacobi et al*. [1998] and references therein). Typical amplitudes and phases for the extracted 5-day, 16-day and stationary waves are shown in Figures 4, 5 and 6. (The altitude profiles of amplitude and phase for the 10-day wave are similar to those for the 16-day waves, but with amplitudes only about half as big. The 10-day waves are not considered further in this paper as we in practice found that they showed no correlation with NLC.) For reliable extraction of waves using filtering we must avoid times when there are rapid changes in the wave amplitudes due to the change of season (wave amplitudes are generally much higher in winter than in summer). For this reason, we restrict out comparison between NLC and planetary waves to the part of the summer when conditions are fairly stable. Inspection of the seasonal changes for all of the years allows us to identify the period from day 165 to day 200 as a suitable time interval.

Before we can compare the waves with the noctilucent clouds, we must find a reasonable way to extrapolate the amplitude and phase of the waves from the upper heights of the meteorological analysis (50-60 km) to the height of the NLC (80-85 km). To estimate the extrapolation to 85 km we consider available models and observations.

5-day waves

First we consider the 5-day waves. Model studies of 5-day waves in the summer mesosphere have been reported by *Geisler and Dickinson* [1976] and *Miyoshi* [1999]. We use the 2 hPa level (ca 45 km) from our meteorological analysis as a reference, and consider first the waves in geopotential height. *Myoshi* [1999] predicts about a 10 times increase in amplitude and a 30 ° decrease in phase angle (westward tilt) up to 85 km altitude for June (reported for 41.5 ° N, only). An 80 ° decrease in phase angle between the ground and 45 km is also predicted. In the simulations of *Geisler and Dickinson* [1976], predictions for all latitudes are available. For solstice, at 60 ° N the phase at 45 km is about 90 ° less than at the ground and by 85 km the phase angle has reduced by a further 90 °. The amplification between 45 km and 85 km is about 20 times. However, both the amplification and the phase tilt are found to be rather sensitive to the background wind conditions. This provides a second reason to restrict our analysis to the mid-summer period, avoiding the early and late seasons when the background wind conditions are changing. *Geisler and Dickinson* [1976] also calculate the effects of the 5-day wave disturbance on temperature – the phase behavior is almost the same as for geopotential height and the disturbance in temperature increases from about 0.5 K at 45 km to 1-14 K at 85 km, depending on background wind conditions.

Figure 4 shows the amplitudes and phases of the 5-day waves we find from analysis of the global geopotential height fields for about the middle of our study interval (day 185). We see that the growth in amplitude is generally small up to the top-heights available in the meteorological data. This is in qualitative agreement with both of the modeling studies mentioned above. We see also that the phase tilts slowly westward with increasing height and is not inconsistent with the model predictions (80 ° or 90 ° between the ground and 2 hPa (45 km).

Regarding observations of 5-day-wave propagation to 85 km height, we have the possibility to compare the waves we find from the meteorological assimilations at 2 hPa with measurements at 85 km for the summer of 2000. For this year, daily temperature estimates for the height interval 85-95 km are available from a meteor radar at 66 ° N, 20 ° E (Kiruna , Sweden). The technique used to derive temperature from meteor echoes is described by *Hocking* [1999], and the Kiruna measurements have earlier been reported by *Kirkwood et al.* [2002]. Figure 7 shows the 5-day planetary wave temperature oscillations found by analysing the meteorological temperature fields for the coordinates of the radar site. These can be compared with the temperature oscillations observed by the meteor radar. The agreement with the model of *Geisler and Dickinson* [1976] is reasonable, with the temperature peaks at 2 hPa lagging 1-2 days (72 –144 deg) behind the peaks seen at 85-95 km. Also the increase in amplitude (ca. 30 times) is of the same order of magnitude as predicted by *Geisler and Dickinson* [1976] model. These observations agree better with the latter model than with *Myoshi's* [1999] model. So, we might then expect amplitudes of the

5-day wave (in geopotential height) to increase by a factor about 20 and phase to tilt west by about 90 degrees in going from 45 km (2 hPa) to 85 km.

16-day waves

Next we consider the 16-day waves. These have been modeled by *Forbes et al*. [1995] and also by *Myoshi* [1999]. *Myoshi* [1999] found that there appears to be no continuity between waves at low altitudes and high altitudes in the summer hemisphere. Amplitudes at low altitudes are small while amplitudes above 90 km become large and appear to be connected to the waves in the southern hemisphere at high altitudes. *Forbes et al*. [1995] found a similar result, with penetration of 16-day waves into the summer hemisphere at mesopause heights depending on the presence of weak westerlies in that region. *Myoshi 's* [1999} model results for summer show maximum amplitudes of about 20 m (geopotential height) at lower stratospheric heights and up to 40 m at mesopause heights. In the *Forbes et al*. [1995] model, the amplitudes are about 5 times higher. Our observed lower-stratosphere amplitudes (Figure 5) are between the values given by these two models. The model amplifications, about a factor 2 between stratospheric maximum and 86-95 km translate to about a 10 times amplification between 2 hPa and 85-95 km. Unfortunately, neither model study provides information on the expected phase shift between the 2 hPa level and 85 km.

To estimate the phase tilt we have again to use observations. *Espy and Witt* [1996] have reported observations of large-amplitude 16-day waves in temperature, in summer, at 85-95 km altitude and ca. 60 ° N latitude during the summer of 1992. We have compared *Espy and Witt's* [1996] published time-series with the 16-day planetary wave signal at 2hPa in the UKMO meteorological data. We find that the temperature maximums and minimums at 85-95 km altitude appear 1-3 days before the planetary-wave temperature maximums at 2hPa. This is consistent with a westward phase tilt of about 45°. The amplitude of the temperature wave at 85-95 km is about 15 times that at 2hPa.

Stationary waves

Finally we consider the stationary waves. Stationary waves are generally expected to have a phase tilt towards the west with increasing height but their exact height structure is expected to be dependent on the background winds [*Andrews et al*., 1987, ch 5]. Detailed model studies so far have largely concentrated on stationary waves during winter, when their amplitudes are much larger than in summer. *Andrews et al*. [1987] find large differences between hemispheres even when considering only winter. The differences are greatest below the stratopause and winter waves in both hemispheres have similar westward phase tilts of about 30 degrees between the stratopause (45 km) and 85 km. *Volodin and Schmitz* [2001], have modeled stationary waves for both summer and winter but their results are not reported in sufficient detail to be able to determine the phase shift or the amplitude increase from 45 km to 85 km. However, they find that maximum amplitudes at about 85 km height occur at about 30 ° N and are about the same as amplitudes at the lower-stratosphere maximum (at about 16 km) with a deep minimum between.

Figure 6 shows the amplitudes and phases of the (quasi-)stationary waves we find from analysis of the global geopotential height fields for about the middle of our study interval (day 185). We see that the amplitudes have a maximum below 100 hPa (16 km) , decrease to a minimum at about 10 hPa (30 km) and then increase again up to the top of the available height coverage. This is in reasonable agreement with the predictions in *Volodin and Schmitz* [2001] July model, except that the increasing amplitude above 30 km is predicted by the latter model to occur rather higher up (i.e. above 50 km). This discrepancy means that we cannot rely too much on the latter model results to extrapolate our wave amplitudes to 85 km altitude. Regarding phases, we see that there is generally a small westward tilt between the ground and the top of the meteorological analyses, consistent with the basic expectation for stationary waves [*Andrews et al*., 1987]. However, there is no available model prediction to allow a quantitative comparison nor to estimate the further phase tilt between 45 km and 85 km.

Observations of stationary planetary wave amplitudes and phases at 90-110 km height have been made by the WINDII instrument on the UARS spacecraft. *Wang et al*.

[2000], have published an analysis of stationary waves with zonal wave numbers 1 and 2 for the S. hemisphere summers 1991/92, 1992/93, 1993/94 and 1995/96. Although these are for the S. hemisphere, we might expect them to be similar to those in the northern hemisphere at least in the mesosphere (as is the case for winter conditions, according to *Andrews et al*. [1987]). To compare with *Wang et al*.'s [2000] observations for summer solstice conditions, we include in Figure 6 the amplitude and phase profiles for stationary waves in mid-January at 60 ° S for 1992, 1993 and 1994 (from the TOVS analysis). We see that these show phases at the 2 hPa level between 0.5 and 1 radian (30 ° – 55 °), indicating that the highest geopotential heights associated with the stationary wave at 60 ° S are located at longitudes 30° – 55 ° East. Wang et al. find maximum westward winds at mid-latitudes (southern hemisphere) at 90-100 km altitude at longitudes of about 40 ° west. This longitude of the westward wind maximum should correspond to the longitude of maximum upward deflection of the geopotential heights. So it seems that the stationary waves are tilted westward with increasing height with a 70-95 ° phase shift between 2 hPa and 90-100 km. Regarding amplitudes, *Wang et al.* [2000] find the amplitude to be about 5 ms^{-1} in meridional wind (at 60 ° S). Assuming geostrophic winds, this corresponds to a wave amplitude of about 200 m in geopotential height. This represents an amplitude increase by about 5-10 times compared to the amplitude at 2 hPa (45 km). Compared to the lower stratosphere (see Figure 6) the amplitude is only 1.3 - 2 times greater at 90-100 km, in reasonable agreement with the modeling work of *Volodin and Schmitz* [2001]. In conclusion, we might expect stationary planetary waves to grow in amplitude by about a factor 10 and to tilt westward by about 90 ° between 2 hPa and 85 km height.

Correlation between Planetary Waves and NLC

To study whether there is any relation between planetary waves and noctilucent cloud sightings we proceed as follows. The amplitude and phase of the' 5-day', '16-' and 'stationary' waves at 60 ° N and 2 hPa pressure are found using the meteorological analyses as described above (for 12 UT every day between day numbers 165 and 200 and for every year from 1979 to 2000). The displacement (in geopotential height) due to the wave motion at 0 ° longitude , 85 km height and 24 UT is found using , as a first estimate, 10 times amplitude magnification for all waves and and 90° , 45° and 90° westward phase shifts for the 5-day, 16-day and stationary waves, respectively. The range of displacements represented is divided into a suitable number of sub-intervals and the number of nights when the corresponding displacements were present is counted. Then the same subdivision is made of nights when noctilucent clouds were reported. The ratio of these two numbers gives the probability of observing a noctilucent cloud as a function of the geopotential height displacement due to the waves. The results are shown in Figure 8. Clearly there is very little, if any, correlation.

Given our uncertainty in the phase extrapolation between 2 hPa (45 km) and 85 km it seems worthwhile to first check whether we would get different results with other phase extrapolations. So next we assume a series of different phase shifts, differing from our first estimates by between –180 ° and +180 °. In each case the regression between probability of NLC observation and wave displacement is calculated. The gradients of the regression lines and the correlation coefficients (squared) for each wave component separately, and for 5-day, 16-day and stationary waves together, are shown in Figure 9. In order to assess the confidence of the correlation coefficients we have made tests replacing the real noctilucent cloud observations with random numbers. Each day (from day 165 to 200) of each year (1979-2000) is randomly assigned as a day of NLC observation or not, with a statistical probability of 50% for either state. The random ’observations’ are then processed in the same way as the real observations, for different possible phase shifts, as in Figure 9. 1000 trials have been made with different sets of random ’observations’. The maximum correlation reached for any phase shift was recorded for each trial. This allows us to determine confidence limits, e.g the 90% confidence limit corresponds to the value of correlation coefficient (squared) which was exceeded in 10% of the random trials. 50%, 90% and 99% confidence limits are shown in Figure 9.

The same computations were made also for the 10-day waves. These are not shown in Figure 9 since the correlation did not exceed the 50% confidence limit, for any phase shift. We can conclude that the 10-day waves are either unimportant in this context, or their phases and amplitudes at the height of NLCs (80-85 km) are not systematically related to the phases and amplitudes at 2 hPa. This might be because the amplitudes are too small, or because our filter band for '10-day' waves includes also other waves which prevent any correlation being visible.

For the 5-day, 16-day and stationary waves we find a maximum correlation (with positive regression) at phase shifts around 90 °less than our first estimates and maximum anticorrelation (negative regression) with phase shifts around 90° more than our first estimates. In all three cases, the correlations reach or exceed the 90% confidence level. There is little difference in the correlations for the different waves – both the correlation coefficients and the gradients of the regression lines are similar in all three cases. This tells us that the relative phase shifts (between the different waves) and relative amplitude magnifications must be similar to our first estimates (although not necessarily the absolute amounts we have assumed). So we can consider the combined effects of all three disturbances by applying the same relative phase shifts and amplifications as our first estimates. This is also shown in Figure 9 (uppermost panels) where it can be seen that it leads to correlation coefficients exceeding the 99% confidence level (close to -90° and +90 ° phase shifts away from out first estimates).

These results are, at first glance, rather surprising. High displacements in geopotential heights in the waves correspond to high temperatures. If the true phase shifts between 45 km and 85 km are less than the 90°/45°/90° we first assumed (for 5-day, 16-day and stationary waves, respectively), then Figure 9 means that the probability of observing NLC is highest in the warmest part of the waves. We would rather expect the opposite. To get an anticorrelation between geopotential hight and NLC, the phase shifts between 2 hPa and 85 km would have to be much more than 90°/45°/90°, i.e. by 50°-100°. Even though we cannot be sure of the wave phase extrapolation from 2 hPa to 85 km, on the basis of the models and observations discussed above, it seems unlikely that we have under-estimated them by such a large amount. We must consider other possible explanations.

One possibility is that the correlation has nothing to do with conditions at noctilucent cloud heights but reflects a correlation of tropospheric weather (viewing conditions) with planetary waves. The spread of observing locations is some insurance against this but the possibility cannot be ruled out completely. Further investigation of this possibility is beyond the scope of the present paper.

A second possibility is that the phase shift between 2 hPa and 85 km is indeed close to our first estimates, and that the correlations we observe are due to transport effects rather than local temperature in the wave fields. Since we are dealing with waves whose zonal wavelength is the whole length of a latitude circle, the maximum negative zonal gradient in geopotential height, which means the maximum southward wind, lies 90 ° east in longitude from the maximum in geopotential height itself. If we correlate NLC observations with meridional wind instead of deflection in geopotential height, and assume our first-estimate wave-phase shifts between 2 hPa and 85 km, we will get the correlation coefficients shown for 90 ° higher phase shifts in Figure 9. It can be seen from Figure 9 (upper left panel) that the correlation coefficients for the 5-day, 16-day and stationary waves taken together, exceed the 90% confidence level for phase shifts throughout the interval +50° to +110° above our first estimates. If the meridional wind is the factor responsible for the correlation, the wave phase tilt must be 90° degrees less than this, i.e. 50° –110°/ 5° –65°/ 50° –110° for the 5-day, 16-day and stationary waves, respectively. This is consistent with our expectations based on the models and observations discussed in the previous section.

The maximum southward wind could be expected to correspond to the part of the wave field where clouds arriving at 60 ° N have come from the most northerly location. Detailed modeling of nucleation, growth, and sublimation of NLC particles as they are transported by mean and tidal winds have been made by *Gadsden [1998b]*. The wind field which we predict on the basis of the planetary waves are rather different from the zonal-mean winds used in the latter study. However, the basic process of cloud nucleation at the height of coldest temperatures (around 87 km) followed by growth and gravitational settling, should be the same. According to *Gadsden [1998b]*, then, the cloud particles should grow for about 12 hours following nucleation and by this time have settled to about 82 km altitude where the temperature becomes too high, and the particles sublime. An increase in water vapor concentration and decrease in temperature at NLC heights between mid- and high-latitudes is to be expected. So, the super-saturation needed for ice nucleation is more likely to be found at higher latitudes. This can form the basis of a dependence of NLC appearance on meridional wind speed. As pointed out by *Gadsden [1998a]*, the observers contributing to the data-base we use here, rather often see the southern edge of the NLC, presumably corresponding to the sublimation limit described above. Air masses arriving at this limit from the north are more likely to include noctilucent clouds, than those arriving from the south , since the latter are less likely to have been subjected to the super-saturation needed for nucleation Air masses travelling most rapidly from the most effective nucleation region further north are least likely to have lost their NLC by gravitational settling to the evaporation level.

Modeled air -parcel trajectories are illustrated by Figure 10 (in the horizontal direction on the 4500 K isentropic surface, which is at about 85 km altitude at 70 ° N and 83 km altitude at 60 ° N). Here we have assumed the location of maximum geopotential height in the stationary wave to be 10 ° west, i.e. 90 ° west of the average location at 2 hPa (80 ° east, see Figure 6). The stationary wave has a maximum amplitude of 250 m at latitude 60 ° N, similar to the observations of *Wang et al*. [1997], and consistent with an amplification of 5-10 times relative to the 2 hPa (45 km) level (see Figure 6).   A 5-day wave with maximum amplitude 300 m at 80 ° N has been added (based on the model results of *Geisler and Dickinson* [1986]). At 60 ° latitude, the amplitude has fallen to about 250 m, or about 3-30 times the amplitudes we find at 2 hPa (Figure 4). The 5-day wave starts with the ridge in geopotential height at 0 ° longitude and moves westward around the globe. The combined geopotential height wave-fields at 12 h intervals are shown in the different panels. Further, a mean zonal wind of 40 ms^{-1} (westward) is added, and a mean meridional wind of 6 ms^{-1} (southward). Back trajectories for 12 h preceding arrival at different longitudes (all at 60 ° N) at different phases of the 5-day wave are illustrated. (Note that the 16-day wave is not included separately - on 12-h time scale of the trajectory simulations, it can be considered as part of the stationary wave.) It is clear that the wave phase at arrival makes a substantial difference to the history of an air mass arriving at the location of the observations (60 ° N, 0 ° E)

Figure 11 illustrates in more detail the origin of air parcels arriving at 60 ° N, 0 ° E as a function of the meridional wind at the place/time of arrival (due to the 5-day and stationary waves in Figure 10). Two results are shown – one for a mean westward zonal wind of 40 ms^{-1}, the other for 10 ms^{-1}. The result in both cases is an elongated ellipse, with the narrower ellipse corresponding to 40 ms^{-1} wind. The latitude of the center of the ellipse depends mostly on the meridional wind due to the stationary wave, with a small effect of the zonal wind (as the trajectory crosses more or less of the stationary-wave wind field during the 12 h travel time). The upper and lower traces of the ellipse are due to the varying winds during the passage of the 5-day wave (increasing and decreasing winds respectively). The length of the ellipse (latitude difference between top-left and bottom-right) depends on the amplitude of the 5-day wave. The breadth of the ellipse is determined by the difference between the mean zonal wind and the westward phase speed of the 5-day wave (46 ms^{-1}). With a 40 ms^{-1} mean wind, air parcels remain in almost the same phase of the 5-day wave throughout their travel so there is little difference between the upper and lower traces of the ellipse - it approaches a straight line. According to CIRA-86 [*Fleming et al.*, 1990] we should expect zonal winds at NLC heights to be closer to 40 ms^{-1} than to 10 ms^{-1} so that the relation between meridional wind and latitude of origin of air parcels arriving at the observation location should be close to linear.

Figure 12 shows the observed relationship between the probability of observing NLC and the meridional wind speed at the time and location of observation, assuming 90°/45°/90° wave phase tilt between 2 hPa (45 km) and the height of the NLC (85 km) for the 5-day/16-day/stationary waves, respectively. There is now a visible correlation both for 5-day , 16-day and stationary waves separately and for their combined effects. It seems the location of the observations is fortunate in that the meridional winds due to stationary waves are most often southward (negative) so that, despite the fluctuations caused by 5- and 16-day waves, air parcels arrive from the north more often than from the south.

It is clearly of interest to consider whether changes in planetary waves from year to year might explain the decadal cycle in noctilucent clouds. Depending on the phase of the stationary wave over the observation site, the 5-day cycles of increasing and decreasing phase will be more or less likely to bring air-masses from the north rather than the south. The third panel of Figure 1 shows the year-to-year variation in NLC occurrence which we predict from the year-to-year variation in planetary waves (calculated using the regression in the uppermost-right panel in Figure 12). The 10-11 year cycle can also be detected in the predicted occurrence rates (third panel of Figure 1), although the extreme maximums and minimums of the real observations are not reproduced. The lowest panel of Figure 1 shows the difference beween the observed and predicted occurrences, where no distinct cycle can be seen. Figure 13 plots predicted NLC occurrence against observed. The points are rather scattered , and the correlation coefficient is only 0. 4. The points cluster around equality but they are correlated only at the 92% confidence level. So we cannot be sure that the observed yearly NLC occurrence rates really depend on planetary wave activity.

Figure 14a examines the cross-correlation between the predicted NLC occurrences and solar activity. The correlation is almost as good as the one found for the observations in Figure 2b (correlation coefficient about 0.5), with a lag of 1 year between solar activity and NLC occurrence. However, the correlation in Figure 14a reaches only the 85 % confidence limit, i.e. there is a 15% chance that it is due to random noise, not to a true correlation On the other hand, the chance of obtaining, by random chance, such a high anticorrelation at a lag of 1-2 years (rather than an arbitary lag) is a factor 5 less. Figure 14b examines whether the residuals - the difference between the wave-predicted NLC occurrence and the observations - have any solar-cycle component. In this case the correlation reaches only 60% confidence, and may also be due to random chance. Again though, the coincidence in the phase of the correlations in Figures 14b and 2b, increases the statistical confidence. So it seems that changes in planetary wave activity correlated to solar activity might be an explanation for at least part of the decadal cyle in NLC, during the period 1979-2000, but the statistical confidence is not high enough to be sure. Note also that the correlation coefficient in all cases, Figures 2a, 2b and 14a, reaches only a little above

0.5. This means that only 25% of the year-to-year variability in observed or predicted NLC occurrence can be statistically ‘explained’ by solar activity.

Perhaps surprisingly, the solar cycle- planetary wave relationship is clearer than the solar-cycle- NLC relationship. This is shown in Figure 15. The phase of the stationary wave appears to vary with solar activity - at the 2hPa level the ridge in geopotential height lies at around 50° E longitude at low solar activity but moves further eastward to around 90° E longitude at high solar activity. In this case the correlation exceeds the 99% confidence limit.

Discussion and Conclusions

We have found a highly significant correlation (exceeding 99% confidence limits) between the probability of observing NLC in NW Europe on any particular day, and the atmospheric perturbations induced by 5-day, 16-day and stationary planetary waves at the same latitude and longitude. With reasonable assumptions for the phase tilt of the planetary-wave disturbances between the 2 hPa level and the height of the noctilucent clouds, we find that the correlation can best be explained as a transport effect. Noctilucent clouds are most often observed when the wave-induced winds blow most strongly from the north. The correlation with 5-day waves can explain previously reported 5-day periodicities in NLC observations. This provides an alternative to *Sugiyama et al's* [1996] proposal of a 5-day cycle of ice-particle formation and sublimation.

The 5-day and 16-day wave-induced wind fluctuations we find by assuming a 10 times amplification of between direct observations (geopotential height) at 2 hPa and NLC heights, are in good agreement with radar wind observations previously reported in the literature. As can be seen in Figure 12, 16-day waves in our analysis correspond to wind variations of about +/- 5 ms^{-1} at NLC heights, 5-day waves to +/- 10 ms^{-1}. This is in reasonable agreement with the study by *Williams and Avery* [1992] of winds at Poker Flat, Alaska, where 16-day wave amplitudes of 2-6 ms^{-1} and 5-day wave amplitudes of 3-7 ms^{-1} were found close to the summer mesopause. Also, *Jacobi et al.* [1998] have found 5-day and 16-day wind oscillations at summer mesopause heights over Germany (52° N), with amplitudes in summer 3-4 ms^{-1} and 1-2 ms^{-1} , respectively (mean climatology 1983-1995). Although *Jacobi et al.* [1998] and others have found evidence for 10-day waves at mesopause heights, we find no correlation between NLC and planetary waves with periods around 10 days (more exactly, 6-12 days) at 2 hPa. This might be due to interfering waves within the period interval and/or varying upward propagation characteristics. Indeed, *Jacobi et al.* [1998] find that the 10-day wind fluctuations at the mesopause are highly variable in strength and suggest that propagation conditions may only occasionally allow them to reach the mesopause. Both *Jacobi et al.* [1998] and *Williams and Avery* [1992] also found evidence for shorter period waves (particularly a quasi-2-day wave), with amplitude at 95 km reaching 8 ms^{-1}, according to *Jacobi et al.* [1998]. Clearly such high amplitudes would imply a significant effect on noctilucent cloud observations, if our proposed wind-transport- effect is correct, and if the high-amplitudes are present also at higher latitudes and slightly lower altitudes. Unfortunately, the limited time resolution of the meteorological data precludes an extension of the present study to 2-day waves. However, it is clearly an interesting avenue for further research when a sufficiently long time series of high-time-resolution winds becomes available from an appropriate location.

In our study we find that year-to-year changes in the phase of the stationary planetary waves correlate with solar activity (with one year lag). This correlation reaches the 99% confidence limit and provides a possible explanation for the previously reported anti-correlation of NLC annual occurrence rates with solar activity (with 1-2 year lag). An effect of solar activity on planetary waves is perhaps to be expected, since their phase-tilt with height is expected to depend on the background winds in the stratosphere and lower mesosphere. It is by now well established that the background state of the stratosphere varies with the solar cycle [*van Loon and Labitzke* , 2000] and physical explanations through the interaction of solar UV and the stratospheric ozone layer have been proposed [*Shindel et al.,* 1999]. However, detailed modeling of the solar-activity effect on summer-hemisphere planetary-wave phase seems not to have made so far, so the reason for the 1-year lag is still unclear. It should also be borne in mind that our correlation between NLC predictions based on planetary waves and solar activity reaches only the 90% confidence limit and the same can be said of the correlation between predicted and observed NLC annual occurrence rates. This leaves a 10% probability that the solar-cycle dependence of NLC has some completely different origin.

Finally we find no evidence for any substantial long-term increasing or decreasing trend in the annual occurrence rate of noctilucent clouds seen from NW Europe from 1964-2000. A previously reported trend [*Gadsden,* 1990, 1998a] was the result of including a wider longitude and latitude interval (primarily observations from Finland) during the later years . The lack of a trend is in accord with in situ observations [*Lübken* , 2000] which show that there is no significant temperature trend at the mesopause at the slightly higher latitudes (66 ° - 71 ° N) where NLC are expected to form. However, the lack of documented NLC before 1885 [*Thomas et al.* 1989] still must be considered significant. Thomas et al. proposed that a sudden increase of water vapor injected into the upper atmosphere by the Krakatoa eruption in 1883 might explain the sudden start of NLC reports in 1985 . *Gadsden* [1990], on the other hand, has argued that decreasing temperatures due to increased carbon-dioxide concentrations might provide an explanation. In the light of our study here, it is not unreasonable to suggest that there might have been a substantial change in the phase or amplitude of the stationary planetary wave affecting the probability of observing NLC over NW Europe and Western Russia (the main population concentrations at appropriate latitudes). According to *Lean et al*. [1995], solar irradiation was significantly (0.1 - 0.2%) less during the 19th century than during the last 40 years. Since we find significant changes in planetary wave characteristics over recent solar cycles (corresponding to slightly less than 0.1% changes in solar flux), it is reasonable to expect rather larger differences between the last 40 years and the 19th century. This could conceivably have led to wave-induced southerly winds being the norm at NLC heights over Western Europe. This would have severely reduced the possibilities for observing NLC.

The possibility that year-to-year changes in noctilucent clouds may not be due to changes in mean atmospheric composition, does not mean that such composition changes have not taken place. As argued by *Gadsden* [1998a], changes in water vapor concentration might well have led to increased brightness of NLCs but this would not, in practice, be detectable to the observers. The increased radiative cooling expected from increased carbon-dioxide might, in this context, be masked by changes in atmospheric circulation (the temperature at NLC heights is driven far below the radiative equilibrium temperature by adiabatic expansion of upwelling air). We conclude that it is very important to bear in mind that substantial, longitudinal differences in middle atmosphere phenomena may be caused by planetary-wave effects. Extreme care should be taken in interpreting long-term changes and decadal variations which have been observed in a limited longitude sector. These may not be due to zonal-mean trends or cycles but only to longitude shifts in planetary waves.

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References

Andrews, D. G., J. R. Holton and C. B. Leovy, *Middle Atmosphere Dynamics*, 489pp., Academic Press, London, 1987.

Bailey, M. J., A. O'Neill and V.D. Pope, Stratospheric Analyses produced by the UK Meteorological Office, *J. Appl. Meteor. 32*, 1472-1483, 1993.

Cho, J. and J. Röttger, An updated review of polar mesosphere summer echoes : Observations, theory, and their relationship to noctilucent clouds and subvisible aerosols, *J. Geophys. Res. 102*, 2001-2020, 1997.

Espy, P. J. and G. Witt, Observations of quasi 16-day oscillations in the polar summer mesospheric temperature, *Geophys. Res. Lett,. 23*, 10, 1071-1074, 1996.

Espy, P. J., J. Stegman and G. Witt, Interannual variations of the quasi-16-day oscillation in the polar summer mesosphere temperature, *J. Geophys. Res., 102*, 1983-1990, 1997.

Fleming, E. L., S. Chandra, J. J. Barnett and M. Corney, Zonal mean temperature, pressure, zonal wind and geopotential height as functions of latitude, *Adv. Space Res., 10* , (12)11-(12)59, 1990.

Forbes, J. M., M. E. Hagan, S. Miyahara, F. Vial, A. H. Manson, C. E. Meek and Y. I. Portnyagin, Quasi 16-day oscillation in the mesosphere and lower thermosphere, *J. Geophys. Res., 100*, 9149-9163, 1995.

Gadsden, M., Observations of noctilucent clouds from North-West Europe, *Ann. Geophys. 3*, 119-126, 1985.

Gadsden, M, and W. Schröder, *Noctilucent Clouds*, 148 pp, Springer-Verlag, Berlin, Heidelberg, 1989.

Gadsden, M., A secular change in noctilucent cloud occurrence, *J. Atmos. Terr. Phys.*, *52*, 247-251, 1990.

Gadsden, M., The North-West Europe data on noctilucent clouds : a survey, *J. Atmos. Sol. Terr. Phys, 60*, 1163-1174, 1998a.

Gadsden, M., Noctilucent clouds seen at 60 ° N : origin and development, *J. Atmos. Sol. Terr. Phy,s 60*, 1763-1772, 1998b.

Gavine, D. M., Noctilucent clouds over Western Europe during 1983 (-1992), *Meteorological Magazine 113 (-122)*, 1984 (-1993).

Gavine, D., Noctilucent clouds over Britain and Western Europe, 1992–1994, *Journal of the British Astronomical Association, 106*, 285 , 1996.

Gavine, D, Noctilucent clouds over Britain and Western Europe, 1995-1997, *Journal of the British Astronomical Association, 110*, 218, 2000.

Geisler, J. E. and R. E. Dickinson, The five-day wave on a sphere with realistic zonal winds, *J. Atmos. Sci.*, *33*, 632-641, 1976.

Hocking, W. K., Temperatures using radar-meteor decay times, *Geophys. Res. Lett. 26*, 3297-3300, 1999.

Jacobi, Ch., R. Schminder and D. Kürschner, Planetary wave activity obtained from long-period (2-18 days) variations of mesopause region winds over central Europe (52°N, 15° E), *J. Atmos. Sol. Terr. Phys.*, *60*, 81-93, 1998.

Kirkwood, S. and A. Réchou, Planetary-wave modulation of PMSE, *Geophys. Res. Lett.*, *25*, 4509 - 4512, 1998.

Kirkwood, S., V. Barabash, B. U. E. Brändström, A. Moström, K. Stebel, N. Mitchell and W. Hocking, Noctilucent Clouds, PMSE and 5-day Planetary Waves : a Case Study, *Geophys. Res. Lett, in press*, 2002.

Lean, J., J. Beer and R. Bradley, Reconstruction of solar irradiance since 1610 : implications for climate change, *Geophys. Res. Lett., 22,* 3195-3198, 1995.

Lübken, F-J., Nearly zero temperature trend in the polar summer mesosphere, *Geophys. Res. Lett., 27*, 3603-3606, 2000.

McIntosh , D.H. and M. Hallissey , Noctilucent clouds over Western Europe during 1973 (-1982), *Meteorological Magazin,e 103 (-112),* 1974 (-1983).

Miyoshi, Y., Numerical simulation of the 5-day and 16-day waves in the mesopause region, *Earth Planets Space, 51*, 763-772, 1999.

Paton , J., Noctilucent clouds in 1964, *Meteorological Magazine, 94,* 180-184, 1965.

Paton , J., Noctilucent clouds over Western Europe during 1965 (-1972), *Meteorological Magazine, 94 (-102),* 1966 (-1973).

Rosenlof, K. H. and R. J. Thomas, Five-day mesospheric waves observed in polar mesospheric ozone, *J. Geophys. Res., 95,* 895-899, 1990

Shindell, D., D. Rind, N. Balachandran, J. Lean and J. Lonegran, Solar cycle variability, ozone and climate, *Science, 284*, 305-308, 1999.

Sugiyama, T., Y.. Murako, H.. Sogawa and S. Fukao, Oscillations in polar mesospheric summer echoes and bifurcation of noctilucent cloud formation, *Geophys. Res. Lett., 23*, 653-656, 1996.

Swinbank, R. and A. O'Neill, A stratosphere-troposphere data assimilation system, *Monthly Weather Review, 122*, 686-701, 1994.

Thomas, G. E. , J. J. Olivero, E. J.. Jensen, W. Schroeder and O. B. Toon, Relation between increasing methane and the presence of ice clouds at the mesopause, *Nature, 338*, 490-492, 1989.

Van Loon, H. and K. Labitzke, The influence of the 11-year solar cycle on the stratosphere below 30 km : a review, *Space. Sci. Rev., 94,* 259-278, 2000.

Volodin, E. M. and G. Schmitz, A troposphere-stratosphere-mesosphere general circulation model with parameterization of gravity waves : climatology and sensitivity studies, *Tellus, 53A*, 300-316, 2001.

Williams, C. R., and S. K. Avery, Analysis of long-period waves using the mesosphere-stratosphere-troposphere radar at Poker Flat, Alaska, *J. Geophys. Res., 97*, 20855-20,861, 1992

Wang, D. Y., W. E. Ward, G. G. Shepherd and D. L. Wu, Stationary planetary waves inferred from WINDII wind data taken within altitudes 90-120 km during 1991-1996, *J. Atmos. Sci., 57,* 1906-1918, 2000.

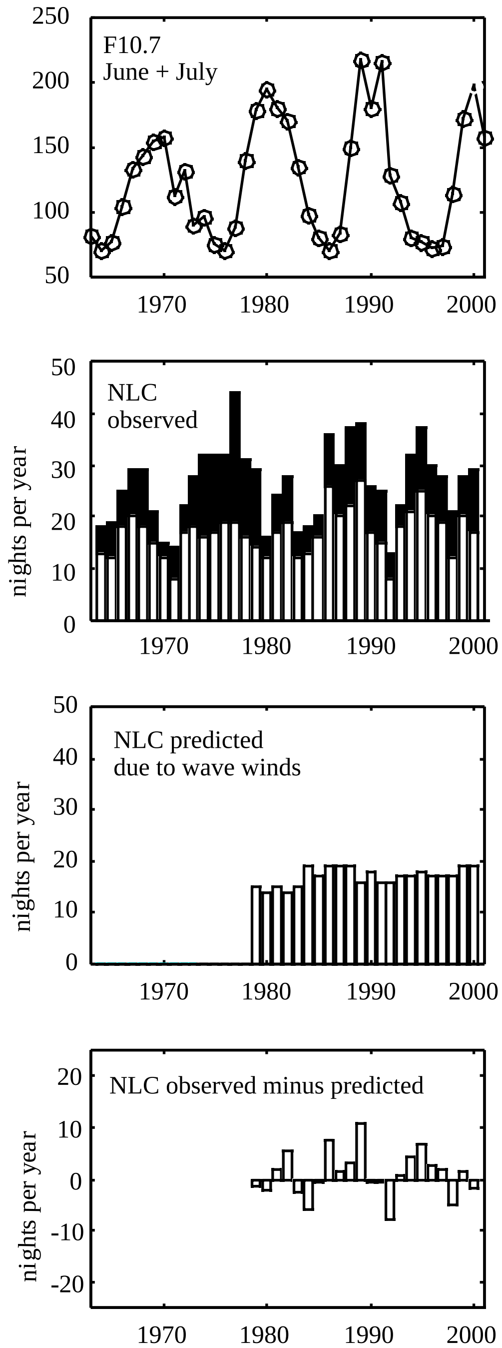


Figure 1 For the years 1964-2000 : Top panel: average solar 10.7 cm flux for the months of June and July (in sfu = $10^{-22}.m^{-2}.Hz^{-1}$); Second panel: number of nights NLC were observed from sites in from Scotland, England, Ireland, Wales, Denmark, and Holland. Solid bars are for the whole summer, white bars for nights between day number 165 (evening) - 201 (morning). Third Panel: Predicted number of nights of NLC observations for nights between day number 165 (evening) - 201 (morning). Prediction is based on planetary-wave characteristics for each year and the regression shown in Figure 12, top-right panel. Fourth panel: difference between observed and predicted numbers of NLC nights.

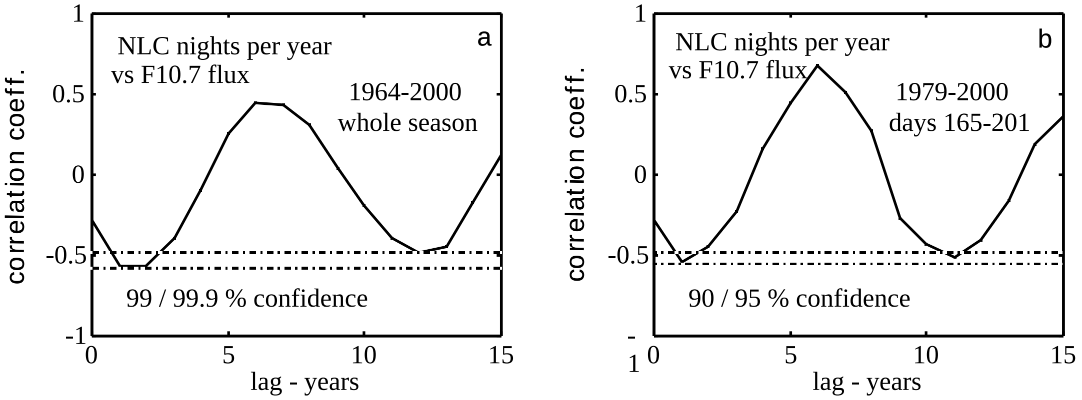


Figure 2 Cross-correlation between solar flux and a) annual NLC occurrence rates 1964-2000; b) annual NLC occurrence rates 1979-2000 for day number 165 (pm) - 201 (am) (solid line).

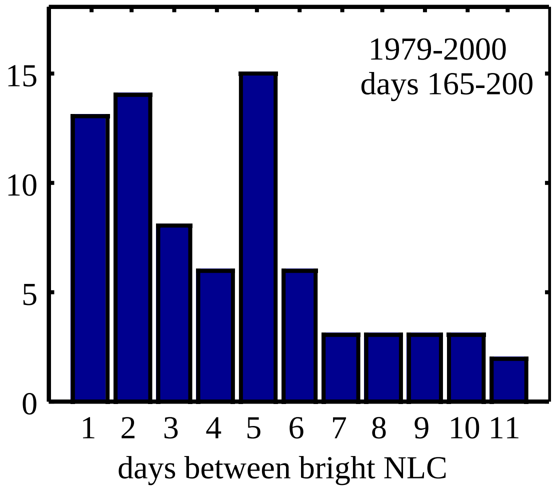


Figure 3. Histogram of the time interval between displays of bright NLC (1979-2000, day numbers 165 – 201).

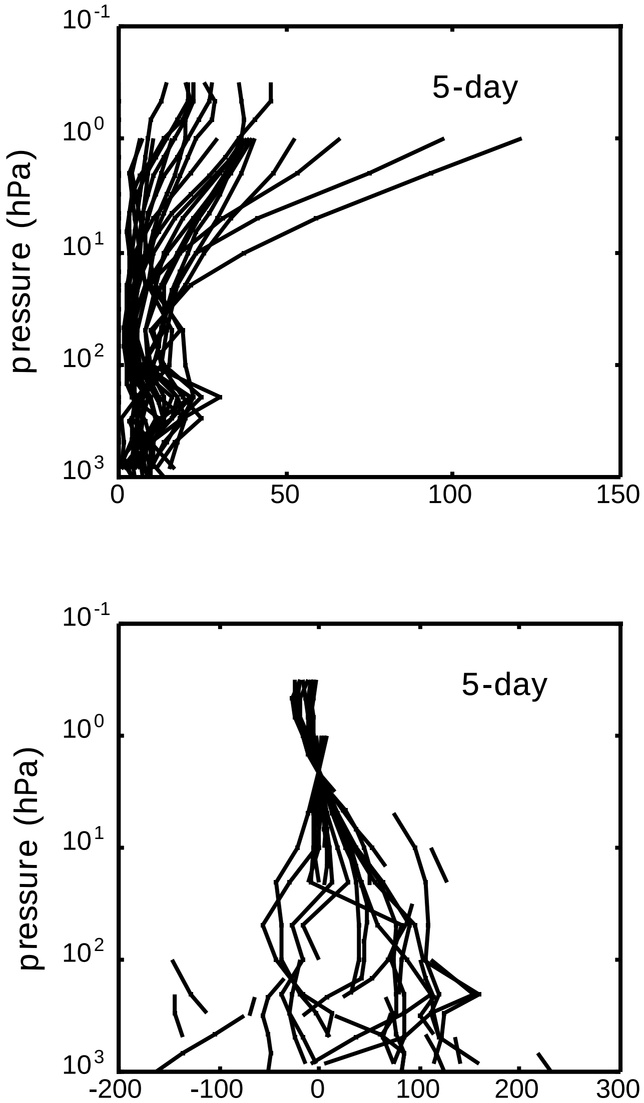
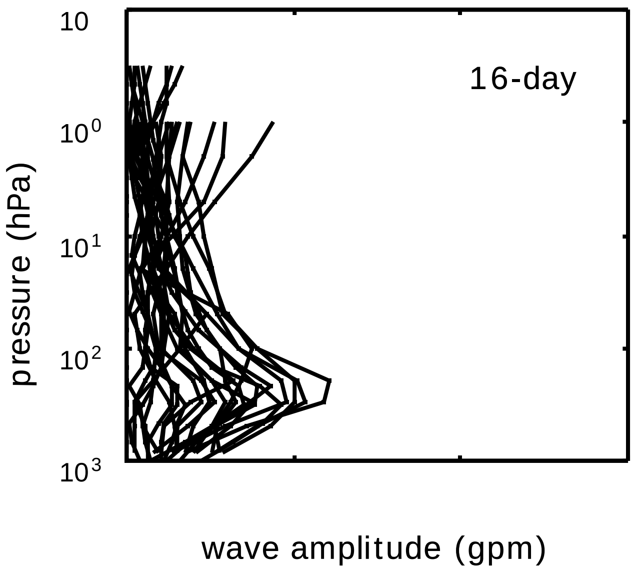


Figure 4 Profiles of 5-day wave amplitudes (geopotential height in m) and phases (relative to 2 hPa) as a function of pressure level from UK Met. Office analyses for 1979-2000, day 185. For latitude 60 ° N.



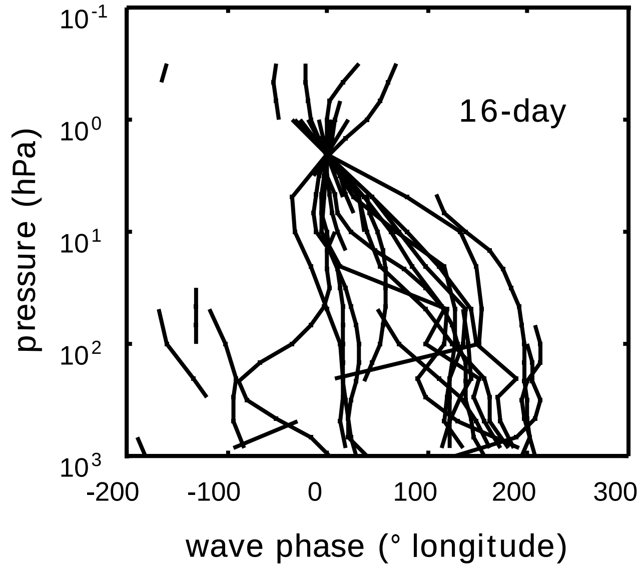


Figure 5 Profiles of 16-day wave amplitudes (geopotential height in m) and phases (relative to 2 hPa) as a function of pressure level from UK Met. Office analyses for 1979-2000, day 185. For latitude 60 ° N.

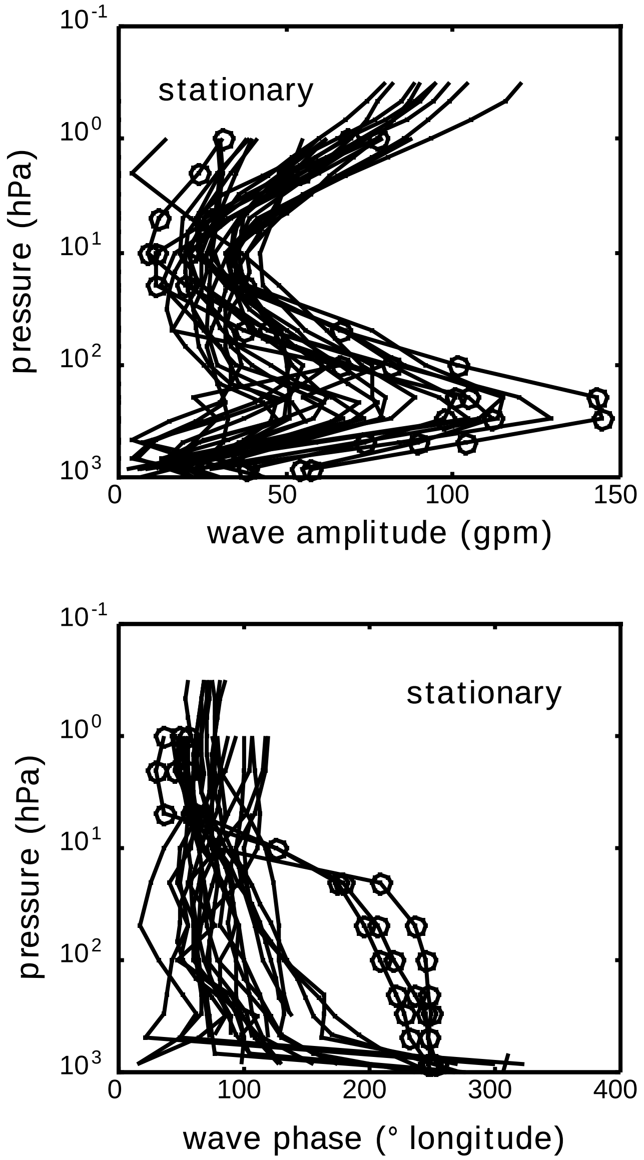


Figure 6 Profiles of stationary wave amplitudes (geopotential height in m) and phases (longitude of ridge) as a function of pressure level from UK Met. Office analyses for 1979-2000, day 185. For latitude 60 ° N. (plain lines). For day 15 and latitude 60 ° S indicated by --o-- .

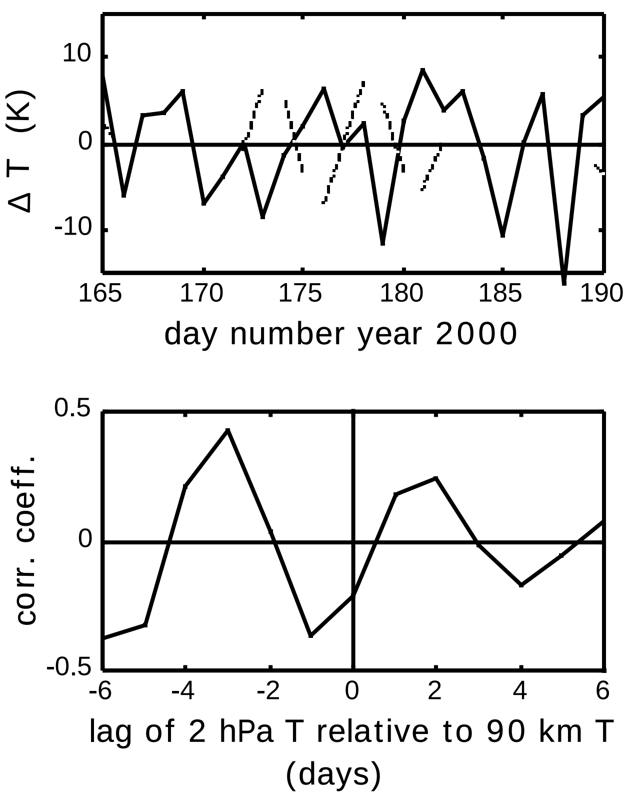


Figure 7 Temperature fluctuations due to the 5-day wave in temperature from the UK Met. Office analysis at 2 hPa compared to temperature fluctuations derived from meteor decay times at 85-95 km. Both for 66 ° N, 20 ° E, day numbers 165-190, year 2000. Note that the temperature fluctuations at 2 hPa are multiplied by 30 before plotting.

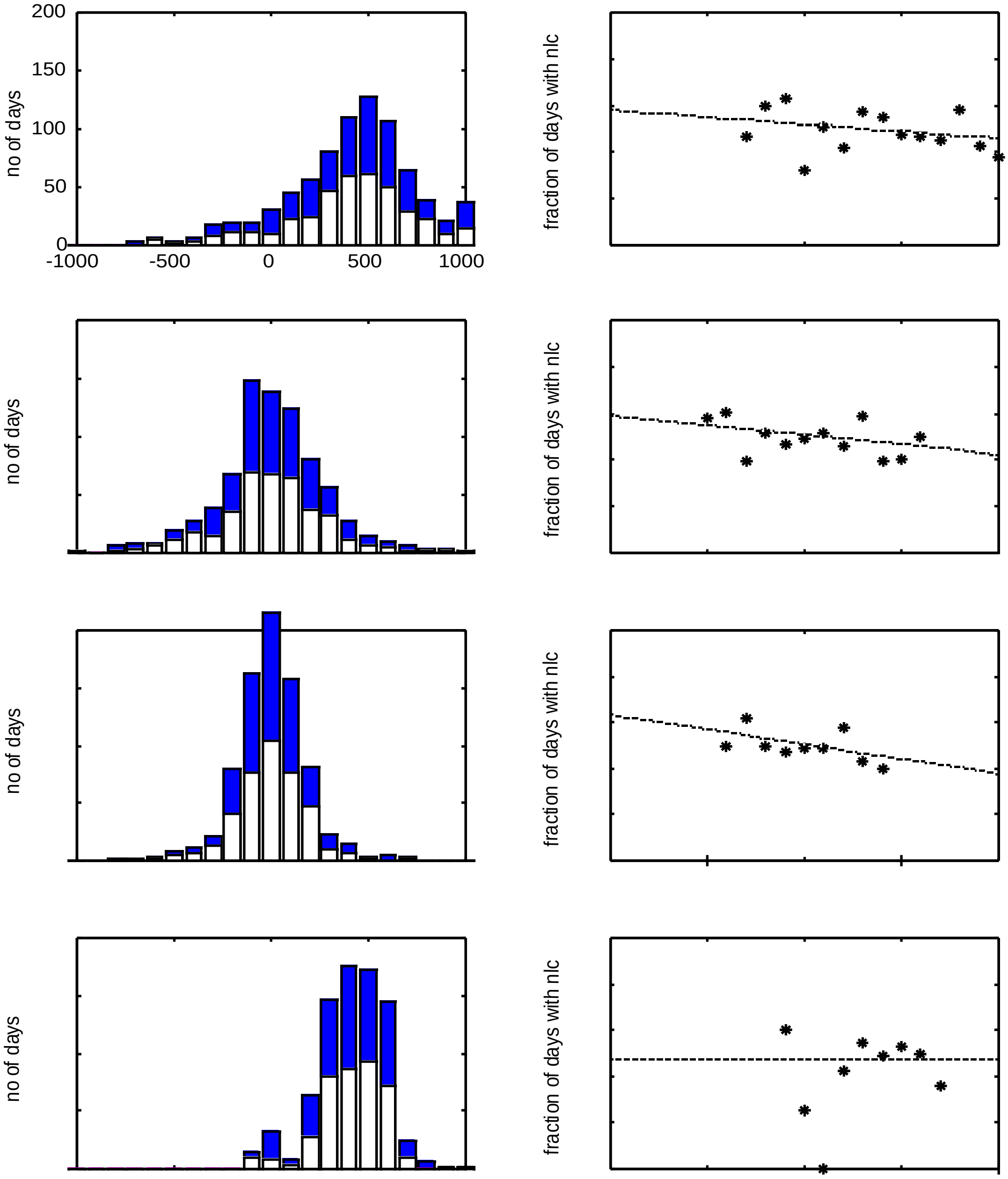


Figure 8 Relationship between occurrence rates of different levels of wave disturbance (displacement in geopotential height extrapolated to 85 km altitude) and of noctilucent clouds, for days 165-201, years 1979-2000. The left hand side shows histograms of the number of nights for each wave-disturbance interval (black) and for the number of nights in each wave disturbance level when NLC were observed (white). Right-hand side shows the ratio of the heights of the two sets of bars in the histograms. Dashed lines on left-hand side are least-squares fit regression lines. . Only wave-disturbance intervals represented by at least 10 days are used for the regression. For further details see text.

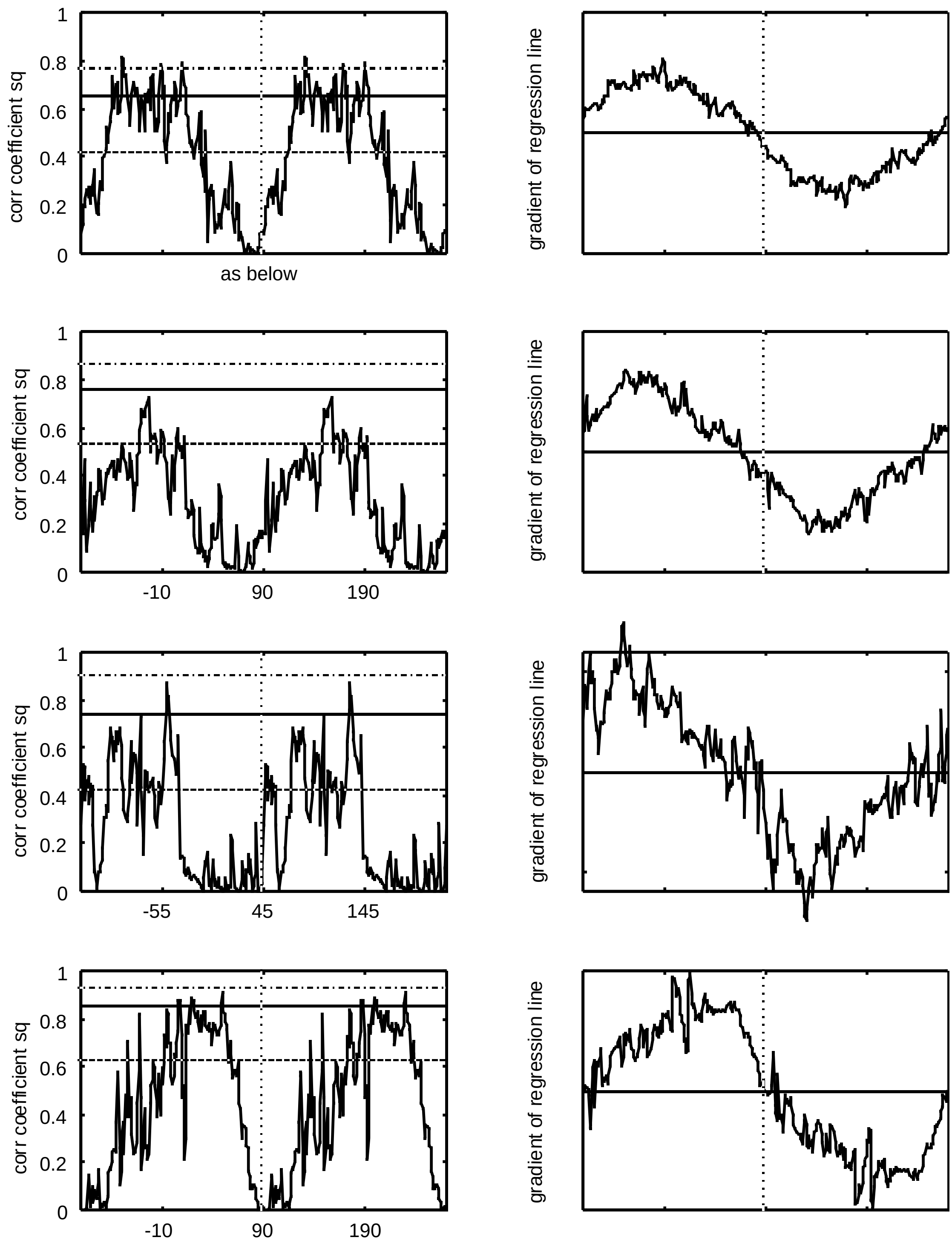


Figure 9 Correlation between wave disturbance level and probability of observing NLC for different assumptions of wave phase shift between 2 hPa and 85 km. Left-hand-side shows the square of the correlation coefficient, Right-hand side the gradient of the regression line. Confidence levels for the correlation are marked : 10 % dashed line, 90 % solid line, 99% dash-dot line.

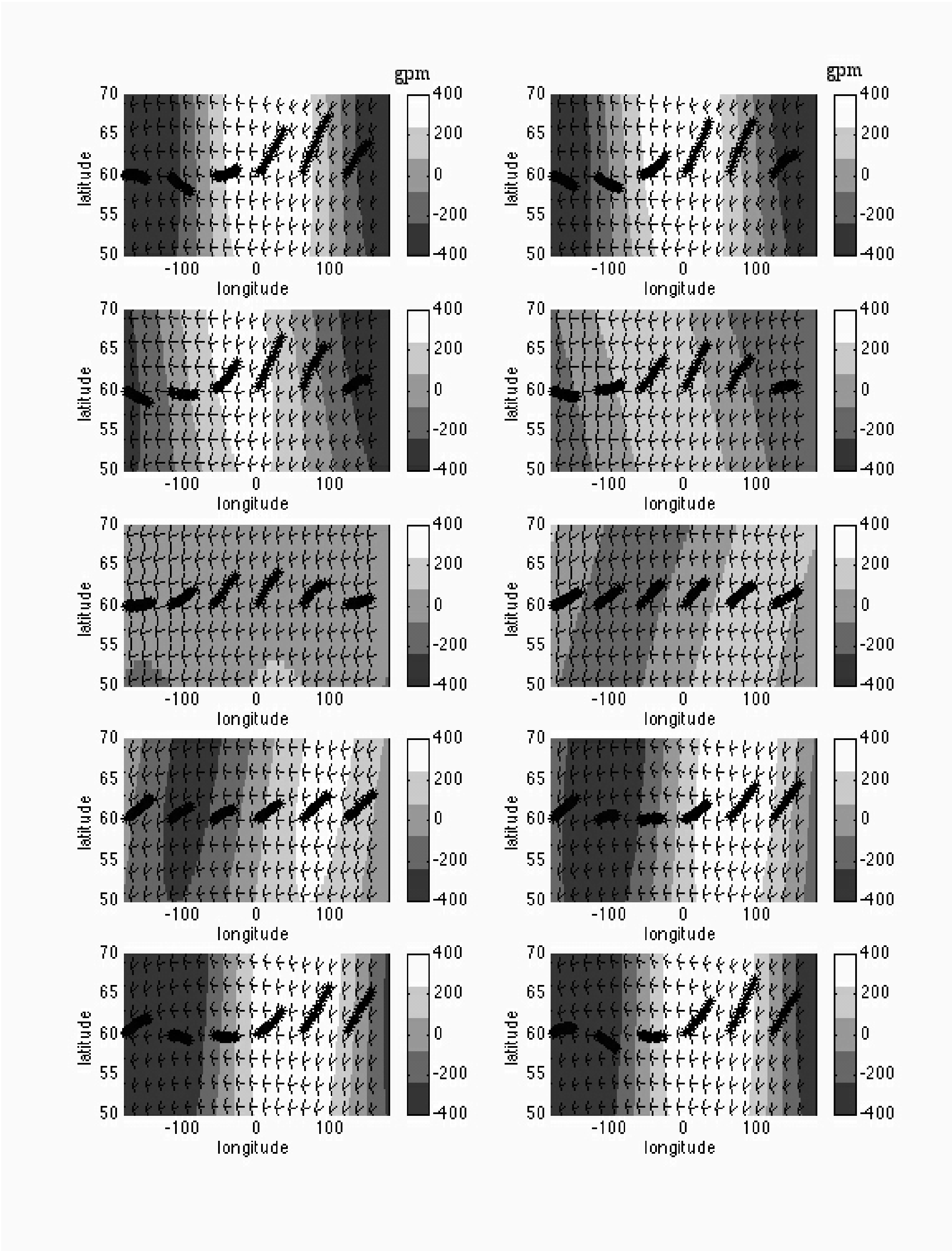


Figure 10 Modeled 12-h back-trajectories (***) for air-parcels arriving at latitude 60 ° N at different wave phases. The wind field is generated by a stationary wave and a westward-travelling 5-day wave, plus a 40 ms^{-1} mean westward wind and a 10 ms^{-1} mean southward wind. Panels show the geopotential height and wind fields due to the combined effects of the two waves, at consecutive 12 h intervals. Back trajectories end when the geopotential height and wind fields are as shown in the panel. For further details see text.

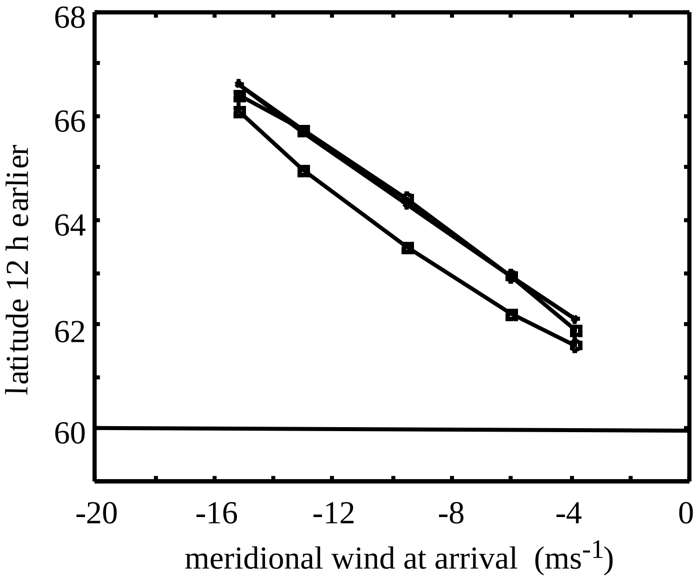


Figure 11 Modeled origin of air-parcels (location 12 h earlier) as a function of wind speed at arrival at 60 ° N , 0 ° E. The narrow ellipse is for the same conditions as Figure 10. The broader ellipse is for a slower uniform zonal wind of 10 ms^{-1} (westward).

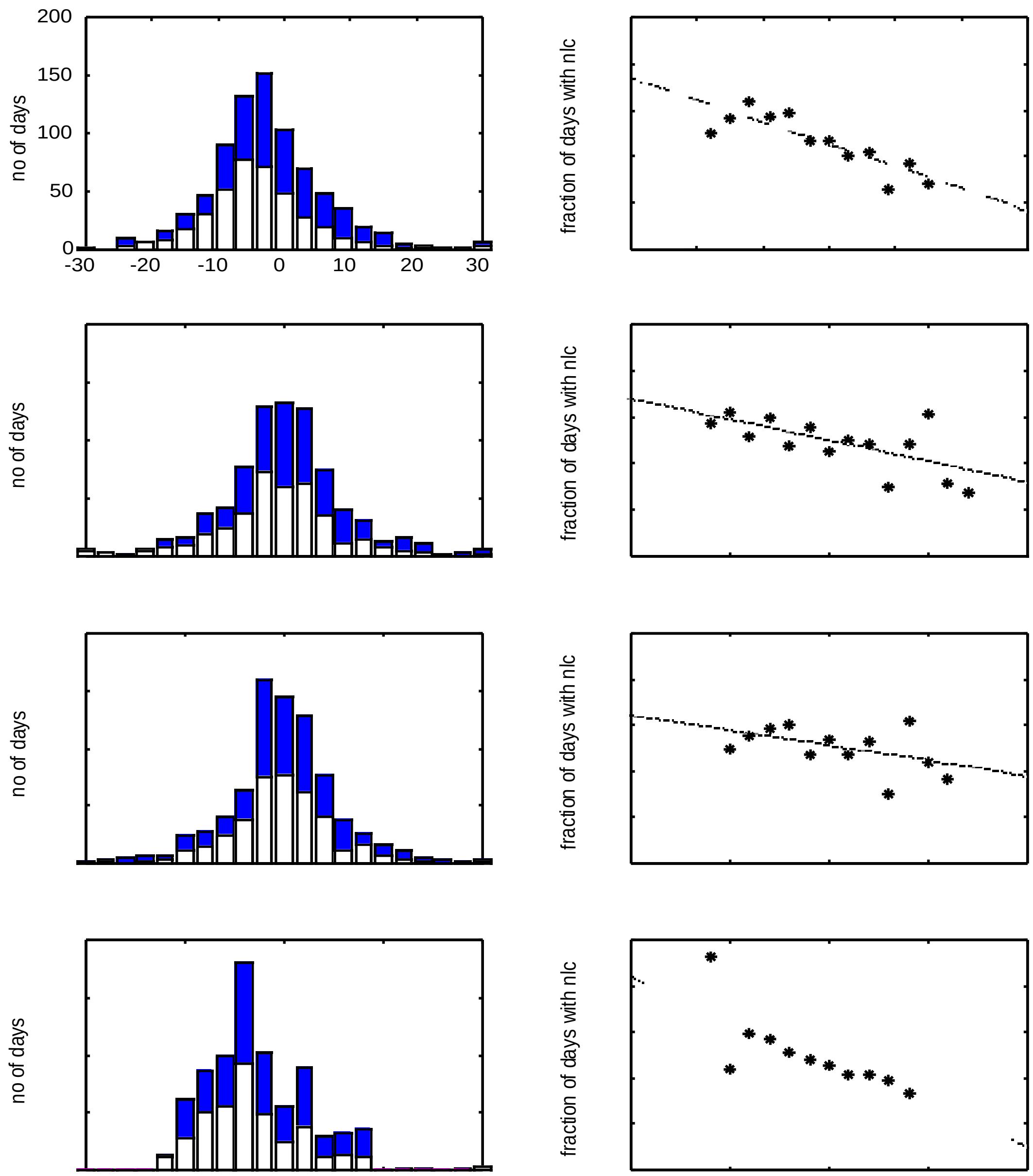


Figure 12 As Figure 8 but for meridional wind extrapolated to 85 km altitude (wave components only). For further details see text.

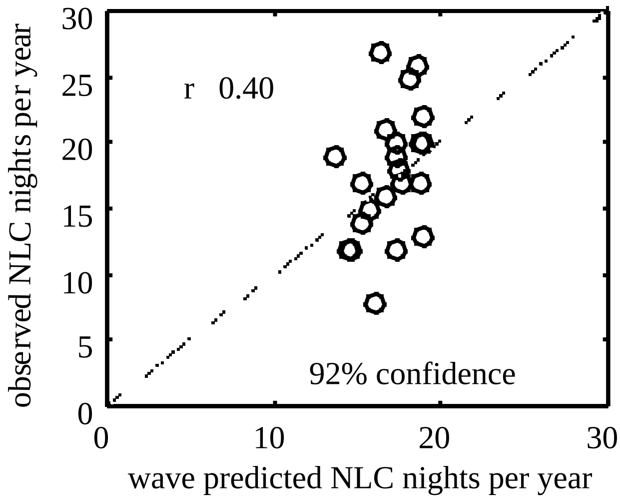


Figure 13 Comparison of predicted nights with NLC (on the basis of wave conditions) and observed nights of NLC (the same data as are shown by the white bars in the second and third panels of Figure 1, for years 1979-2000)

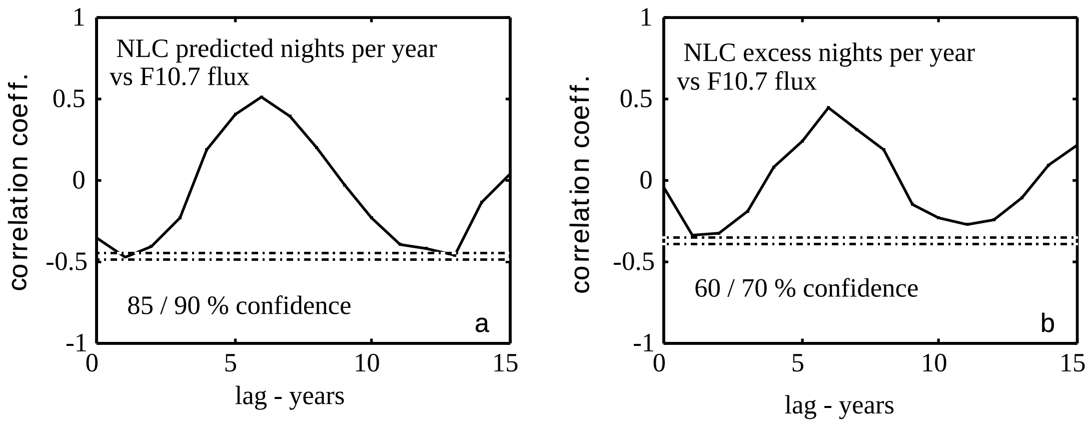


Figure 14 a) Cross-correlations of the predicted number of nights with NLC and the solar flux. b) as a) but for the observed number of nights minus the predicted number of nights (same numbers as fourth panel of Figure 1)

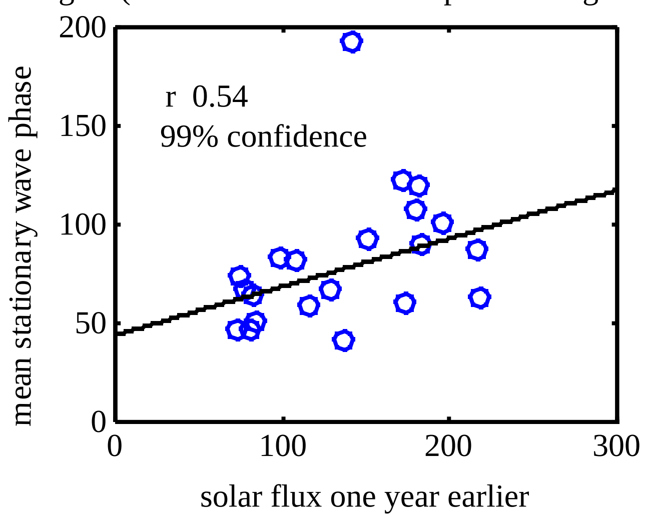


Figure 15 Comparison of stationary planetary wave phases with solar flux one year earlier. (The regression is calculated without the outlier at the top of the panel. This phase estimate corresponds to a very low wave amplitude and is not reliable)