

Numerical Weather Prediction

Comparison of Unified Model Snow and Sea-Ice Fields with NESDIS and USAF Data Sets



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A decorative wavy line that starts on the left, dips down, rises up, and then dips down again towards the right.

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6th August 2003

Abstract

The Unified Model (UM) snow cover and sea-ice fraction fields are compared with the Interactive Multisensor Snow and Ice Mapping System daily Northern Hemisphere snow and ice analysis (IMS). The IMS allows NESDIS analysts to produce an accurate map of snow and sea-ice cover using a wide variety of input sources and the results are distributed in a reliable and timely manner. The UM/IMS comparison spans the period 1st January 2002 to 1st August 2003. The UM snow depth and time offset which result in the best correlation with IMS data are found. UM sea-ice coverage is shown to be less extensive than the IMS. It was discovered that, on occasion, climatological sea-ice fields erroneously appear in UM data as well as anomalous, unphysical-looking gaps in the Arctic ice cap. With the onset of winter, UM snow cover forms fractionally too quickly and then melts far too rapidly in the spring. The IMS tends to have more snow cover in North America, Europe and north of the Caspian Sea, whereas, for the 2002/2003 winter, the UM has more snow cover in parts of the Far East. The USAF Northern Hemisphere snow cover and sea-ice analysis is also considered as an alternative source of validation.

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1 Introduction

Snow cover has long been recognised as having important and complex interactions with weather and climate. General circulation models used for climate modelling and NWP have been restricted by computational expense to use simple representations that, at best, capture the broad features of snow cover. Snow radically changes the surface albedo which affects the surface and air temperature. A snow covered surface effectively halts convection and vertical mixing and a strongly stratified boundary layer develops. From the perspective of satellite data assimilation over land, snow cover will affect the first guess radiance calculation, particularly in the microwave.

In this report, the Met Office's Unified Model (UM) snow cover and sea-ice fraction fields are compared with the Interactive Multisensor Snow and Ice Mapping System daily Northern Hemisphere snow and ice analysis (IMS). The IMS allows NESDIS analysts to produce an accurate map of snow and sea-ice cover using a wide variety of input sources and the results are distributed in a reliable and timely manner. The aim of this report is to compare the UM with this data set and highlight any differences. The IMS product does not give an estimate of the snow depth, only the coverage. Another product, the daily USAF Northern Hemisphere snow cover and sea-ice analysis (USAF), does give the snow depth, so, in an attempt to help determine the significance of mismatches between the UM and IMS, the USAF data was also looked at. This work is a continuation of some of the work carried out by Jeff Ridley on snow depth [1].

Section 2 gives a detailed description of the data sets used in the analysis and some technical detail on how they were processed. Section 3 describes the comparisons made between the UM data and IMS data. The UM snow depth and time offset which give the best correlation with the IMS are found. Statistics on the UM and IMS snow and sea-ice cover are presented and the differences highlighted. Section 4 presents the comparisons made with USAF data. USAF snow depth data is discussed but few conclusions drawn. The results are summarised in section 5 while possible future work is considered in section 6. Appendix A documents some of the other snow and ice products that came to light during this study.

2 Unified Model Snow and Sea-Ice Data

The only Unified Model (UM) output used for analysis came from global model runs and will usually be referred to as UM data from here on. Global model data is stored in a regular grid with 432 divisions in longitude and 325 divisions in latitude. The top 432 grid points are all coincident on the North Pole and the bottom 432 points are all coincident on the South Pole (their data values are all equal). The 12Z global model run (`GL.MN.STD.FC.D12Zyyyymmdd`) with a forecast period of zero hours was used for comparison with the other data sets; this choice of data set is explained in section 3.4. The majority of global model data from 2002 onwards is now available on MASS and more is slowly being transferred from the UABRF. The dates analysed for this report were 1st January 2002 to 1st August 2003. Clearly it would be desirable to analyse two complete winters but global model data from outside these dates is still archived on the UABRF on the IBM. Retrieving data from the IBM requires knowledge of both the IBM and Job Control Language with negligible documentation for the novice.

Grid points which correspond to land were identified using the land mask field, STASH code 00030, taken from the 1st January 2003 global model run. The UM fields used for comparison with IMS and USAF data sets were:

Snow Depth – STASH code 00023, in units of kg/m^2 , equivalent to 1 mm depth of water or very approximately 1 cm of snow. This field is generated by UM snow precipitation, so is completely internal to the UM. Every time this field is read in, all grid points corresponding to sea are converted to -1. It was found that all snow depths are recorded as a positive multiple of 0.125, so a check is performed to verify that the data conforms to this format.

Sea-Ice Fraction – STASH code 00031, dimensionless. Sea-ice fraction is an ancillary field derived from an NCEP analysis of SSM/I data. NCEP use the NASA Team Algorithm [2] to generate the analysis. The analysis for two days previously is ftp'd to the Met Office, interpolated to the global model grid, processed to try to remove holes in the sea-ice and sea-ice fractions of less than 0.5 are cut [3][4]. In the resulting field, all land grid points are recorded as missing data (-1.07374e+09), so when the field is first read in, all land points are converted to -1. It is then checked that there are no data not equal to -1. (land) 0. (sea) or 0.5–1.0 inclusive (sea-ice).

The order in which the field data is stored in the pp files changed with the introduction of new dynamics in August 2002. This change is correctly recorded in the pp header but can still catch anyone pulling the data direct from the structure!

Figure 1 shows histograms of snow depth and sea-ice fraction for the 1st January 2003 and figure 2 shows a colour coded map of the snow depth for the same day. The large snow depths over Antarctica and Greenland are designed to ensure they do not run out of ice on long climate runs.

3 Comparison with IMS Snow Cover Data

3.1 Interactive Multisensor Data

Interactive Multisensor data is a product of the Satellite Analysis Branch of NESDIS. The Interactive Multisensor Snow and Ice Mapping System (IMS) is a tool which allows an analyst to visually inspect snow and ice data from a variety of sources and produce a map showing his best estimate of the actual snow and ice cover in one hour or less. IMS has been operational since February 1997. IMS draws on AVHRR, GOES, METEOSAT, GMS, SSM/I, USAF snow analyses, National Ice Center (NIC) sea ice edge charts and surface observations [5]. ‘The IMS incorporates a wide variety of satellite imagery (AVHRR, GOES, SSMI, etc.) as well as derived mapped products (USAF Snow/Ice Analysis, AMSU, etc.) and surface observations’ [6].

IMS supersedes a system of producing weekly maps of Northern Hemisphere snow cover, operational since 1966 (the last weekly snow map on NCEP’s ftp server is dated 22nd March 2000). When NCEP switched from using this weekly product to the USAF daily snow map they saw a reduction in the surface temperature forecast error. An attempt was made at using a fully automated SSM/I daily snow map but it was found that under certain conditions, such as snow in forests, wet snow and

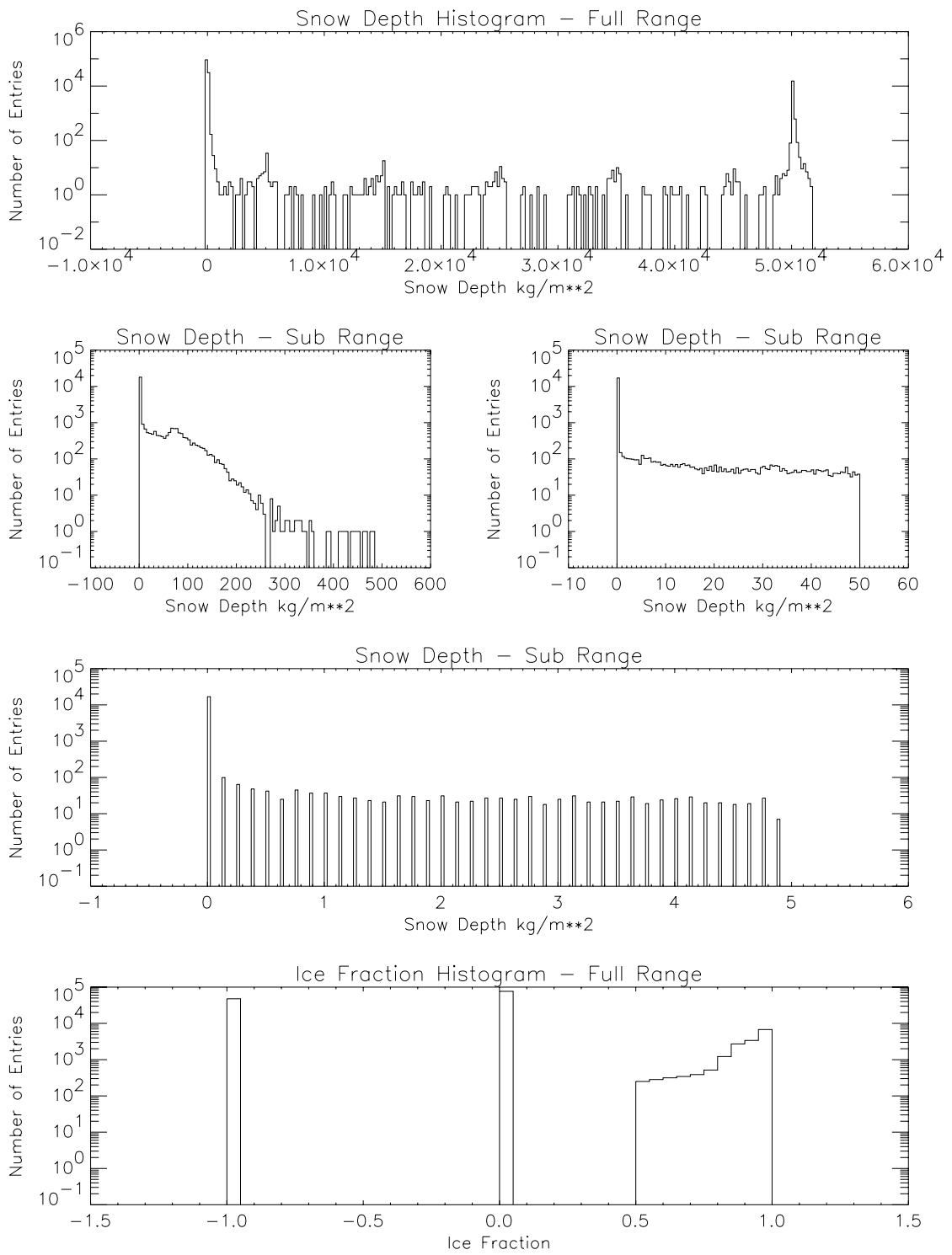


Figure 1: Histograms of UM snow depth and sea-ice fraction for 1st January 2003. All the histograms have a logarithmic y-scale. The top histogram shows the full range and distribution of snow depth values. The next three histograms progressively home in on zero snow depth. All snow depth values are a multiple of 0.125 kg/m^2 . For the sea-ice fraction histogram, -1 corresponds to land and 0 to open sea. Of those grid points containing sea-ice, 87% have a sea-ice fraction of greater than 0.8.

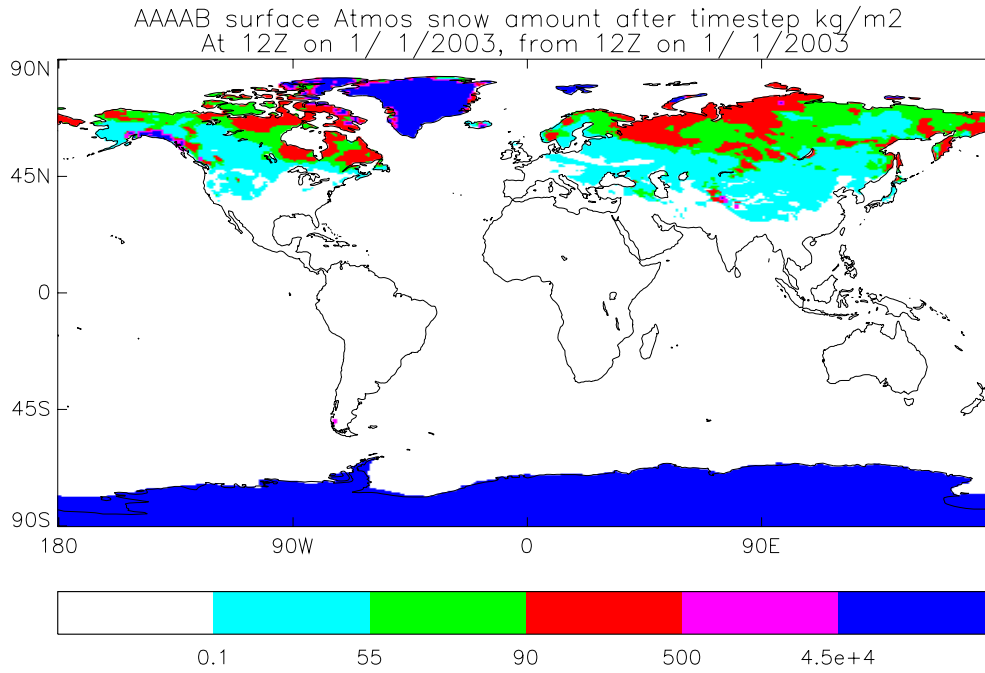


Figure 2: Colour coded map of UM snow depth for 1st January 2003. The values of snow depth separating different colours are in units of kg/m². (The 55–90 band was chosen to highlight the peak in the 2nd histogram of figure 1.)

melting snow, the SSM/I algorithms gave false results'[5]. 'NCEP is unwilling at this time to accept an automated [microwave]-only snow product'[5].

IMS data is available from NESDIS in gif format over the web [6] and in ASCII data file format by anonymous ftp. The ASCII data file usually appears on the ftp server at 21:23 UTC. The data is also available in grib format on the NCEP ftp server at 00:26 UTC. The full ASCII IMS data set, a map for every day since February 1997, was made available for analysis and is updated daily. The 25th and 26th February 2003 and the 26th May 2003 are missing from the data set due to ftp problems.

IMS data consists of a 1024 by 1024 polar stereographic projection. Possible data values for each grid point are: 0–outside northern hemisphere, 1–sea, 2–land, 3–sea ice, 4–snow. Figure 3 shows a colour coded plot of the grid for 1st August 2002 and 1st February 2003. The longitude at the bottom centre of the grid is -80°. An empirical method was used to transform the position on the grid to latitude and longitude; the position of the pole and radius of the equator were adjusted until all Southern Hemisphere data were outside the equator and all Northern Hemisphere data were inside the equator. The pole position was found to be x=511, y=511 and the equatorial radius 501.5. The conversion of x,y to latitude, longitude was done using the Met Office PV-Wave routine UKMO_MAP_PROJ.

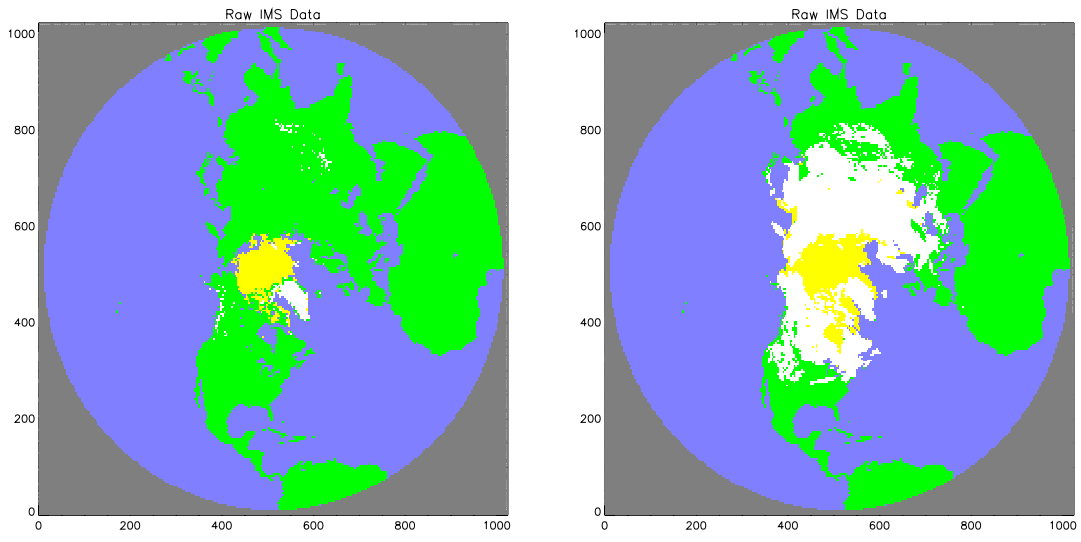


Figure 3: IMS data for 1st August 2002 and 1st February 2003. White indicates snow cover and yellow indicates sea-ice cover. (Only 1/16 of the data points are plotted in each case.)

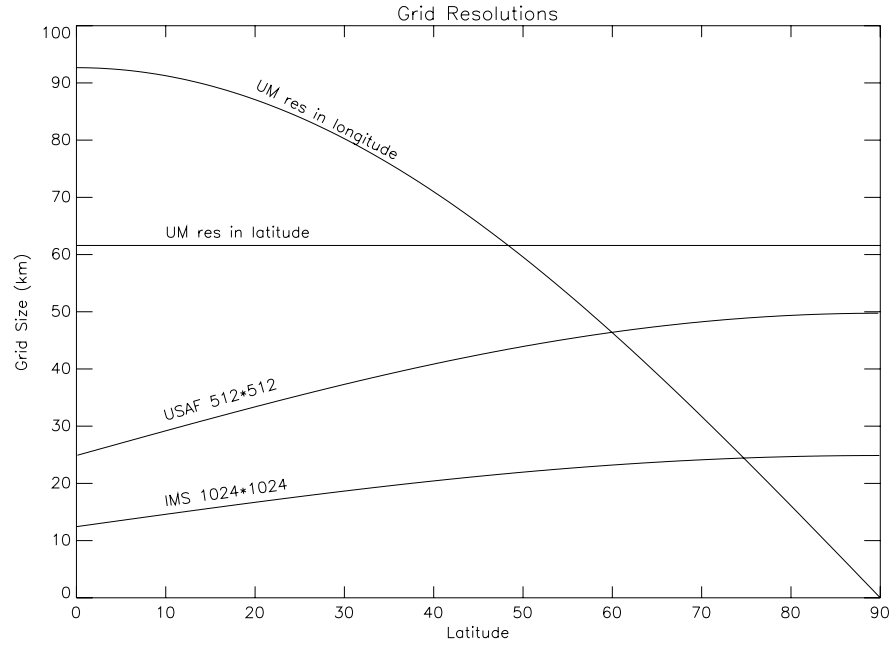


Figure 4: The resolution of UM, IMS and USAF data as a function of latitude.

3.2 Data Resolution

The three data sets studied - the UM global model, IMS data and USAF data - have different resolutions. The USAF data is a polar stereographic projection of the northern hemisphere, like the IMS, but with a grid size of 512×512 . As the latitudinal and longitudinal resolution of the data sets do not vary with longitude, figure 4 shows the resolutions as a function of latitude only. The latitudinal and longitudinal resolutions of polar stereographic projections are the same.

3.3 Conversion to UM coordinates

In order to compare IMS and USAF data with UM data it is necessary to transform one data set into the coordinates of the other. It was decided to carry out the comparison in UM coordinates as the UM is the model we are most interested in and it means that all other UM fields are available for study without modification. As both IMS and USAF data sets were compared with the UM, and it is possible that further data sets will be compared in the future, it is sensible to make UM coordinates the common coordinate choice.

A very simple scheme was used to convert the IMS and USAF data to UM coordinates. Each point on a UM grid was assigned the value of the closest polar stereographic grid point. This results in a bit of duplication around the pole, where the UM grid points are densely packed, and also results in many unassigned IMS and USAF data points, after all the IMS data is 1024×1024 and the USAF data is 512×512 whereas the UM is only 432×163 (for the Northern Hemisphere). The maximum distance between a UM grid point and its associated polar stereographic grid point is under 18 km for IMS and under 36 km for USAF.

3.4 Setting the Snow Depth Threshold and the Time Offset

In order to see if the UM has snow and sea-ice cover in the same areas as the IMS, a threshold must be applied to the UM snow amount and sea-ice fractions. The sea-ice fraction threshold was originally set to 0.499, i.e. just below the minimum value that occurs. It will be shown later that this threshold is a bit too high but as lowering will make no difference to the analysis, it was left where it was. This section describes the method by which the snow threshold was chosen. Although the IMS map is produced daily, it is not clear how old the data used to generate it are. We would therefore additionally like to determine by how much the IMS analysis lags behind the model.

When comparing an IMS map with UM snow and ice fields (using appropriate thresholds) a map can be constructed showing the amount of snow and ice cover and the degree of overlap. Figure 5 shows such a map for 1st January 2003; the mismatch category is where the converted IMS data surface type (i.e. land or sea) does not match the UM surface type. The measure chosen to investigate the degree of correlation between IMS and UM snow cover was the number of land grid points where the IMS and UM *disagree* about the presence of snow cover, ignoring mismatched surface types.

The period chosen to investigate the threshold and offset was 15th January 2003 to 15th February 2003 because the total amount of snow cover was fairly constant (figure 13 on page 17). UM snow fields were iteratively restored from MASS and read in, selecting forecast periods of 0, 3 and 6 hours. For each UM day, hour and forecast period, the field was compared to each IMS file from 3 days before to 6 days in the future and the number of points of disagreement calculated. Doing the comparison this way round minimises the number of MASS retrievals but it is easier to visualise if we consider the IMS file to have been kept constant and the UM day varied from 6 days before to 3 days in the future. Figure 6 shows the degree of anti-correlation for different day/hour/forecast periods and different thresholds. The vertical dotted line indicated the approximate time the IMS data becomes available on the ftp servers (in fact it is 21:23 for the ASCII file and 00:26

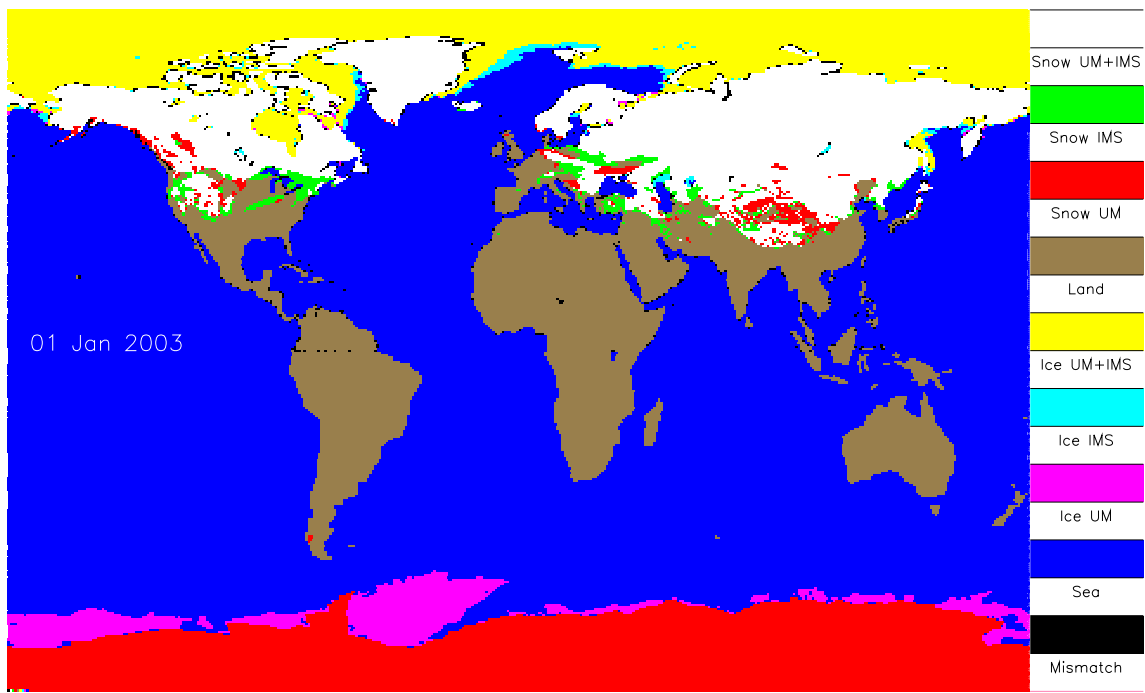


Figure 5: A map showing the snow and sea-ice cover in the UM and IMS data sets and the degree of overlap. The key indicates what each of the colours represent.

for the grib). The range on the scale corresponds to about 10–14% of the total snow cover, so the first important result is that a wide range of settings give very similar results and no particular combination gives spectacular agreement. Two projections from this data set are shown in figures 7 and 8. It can be seen that by the time the IMS data is available it is lagging the model by about 36 hours. It is very likely to be lagging behind reality by the same amount as it seems improbable that snow would start to lie significantly ahead of reality in the model. A puzzling feature of figure 7 is the extent of the asymmetry about the minimum, this is possibly due the source data for the IMS map having a particularly long tail into the past (it is also possible that a tilt has been introduced from the total amount of snow not being completely static). It can also be seen that the amount of agreement varies with the time of day: the correlation is worst with the model Sun directly over the Pacific (0Z), best with the Sun over Tibet (6Z), slightly worse with the Sun over Europe (12Z) and slightly better again with the Sun over America (18Z). From figure 8 the best choice of threshold is 0.225 kg/m^2 . Note that this is simply the threshold which gives the best correlation, it cannot be interpreted as the detection threshold of the IMS because the UM may have a systematic bias which the threshold is compensating for.

If the total amount of snow cover is not static over the period analysed then there will be a correlation between time offset and snow threshold. The same analysis was carried out over the period 1st December 2002 to 31st December 2002 over which time the total amount of snow cover grew a little (figure 13 on page 17), see figures 9, 10 and 11. As the time offset becomes more positive, the favoured threshold increases. When comparing a UM field against the IMS from a few days previously, there is a balance between a higher threshold excluding new areas of snowfall and a lower threshold retaining thin or melting areas of snow. If the amount of snow is

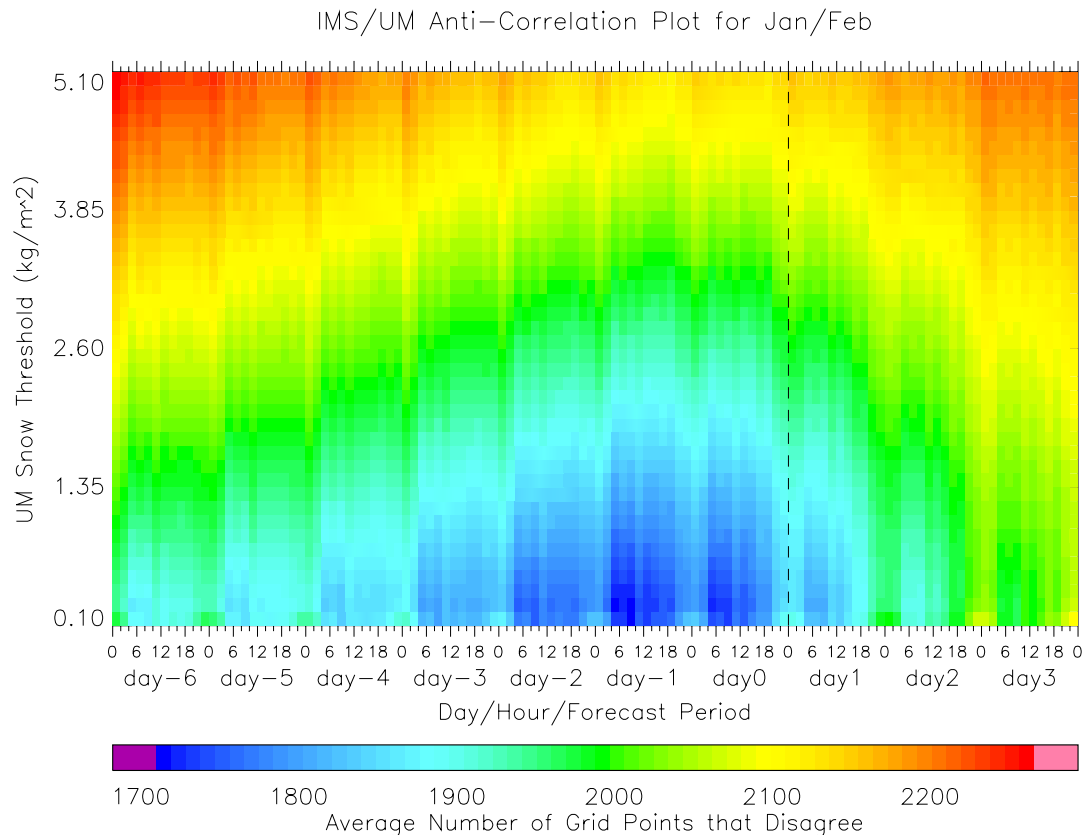


Figure 6: The degree of correlation between an IMS file and contemporary UM snow fields using various snow thresholds in January/February. The range on the scale corresponds to about 10–14% of the total snow cover. The dotted line indicates the approximate time the IMS data file appears on the ftp server.

increasing then the balance will be shifted in favour of the higher thresholds. For the best correlations it would still appear that a threshold of 0.225 kg/m^2 and a time offset of -1 day is a reasonable choice.

3.5 Results

For each day from the 1th January 2002 until the 1st August 2003 the 12Z UM analysis snow and sea-ice fields, with a forecast period of 0 hours, were read in and compared with the next day's IMS data. The 12Z analysis was chosen over the 6Z purely because the date coverage was better. In any case the differences between the 6Z and 12Z are unimportant compared to the differences between the IMS and UM fields (compare figure 7 with figures 12/13). A gif image, like figure 5, was created showing the degree of overlap for each day compared. The gif files were merged together to form an animated gif and a separate web page with a javascript control panel was written to allow a user to scan back and forth through the gif files. These web pages give the user a good subjective overview of the data characteristics [7].

To form a more quantitative assessment of the variability of the snow and ice cover in both data sets, daily statistics were collected on the number of grid points covered with snow/ice, the number of grid points where the snow/ice had melted since the day before and the number of grid points where snow/ice had formed since

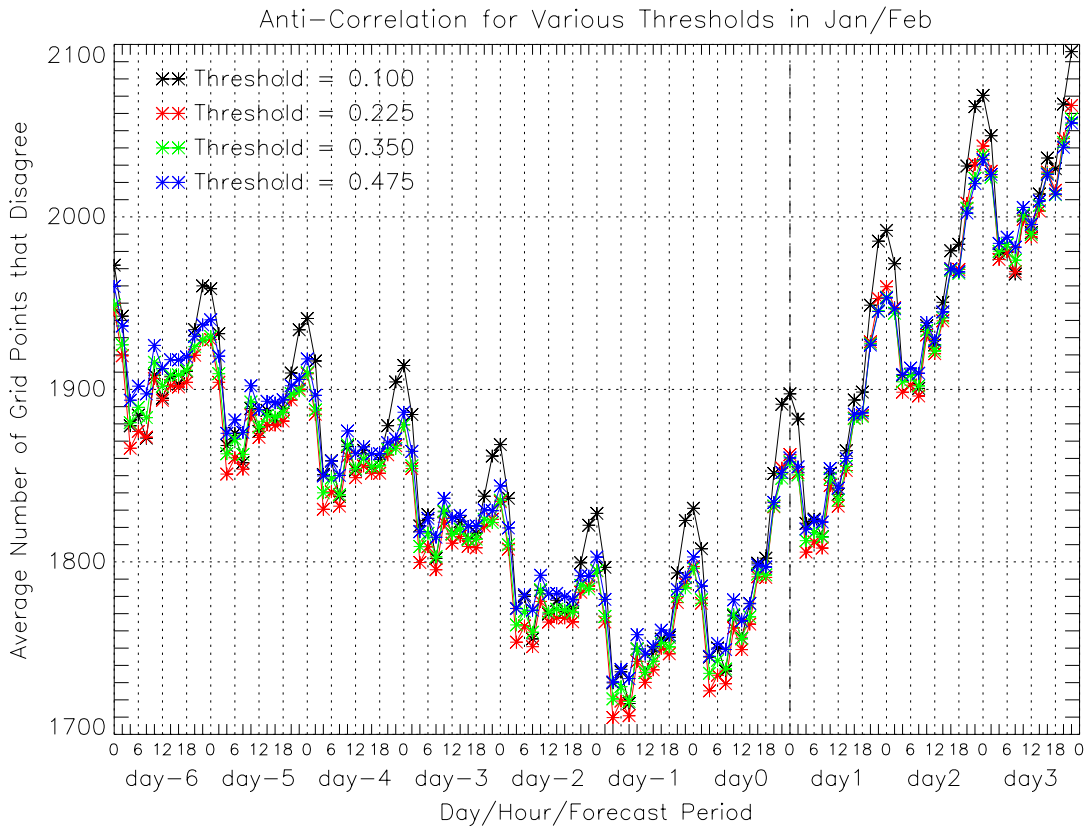


Figure 7: The degree of correlation between an IMS file and contemporary UM snow fields for different snow thresholds in January/February.

the day before. The net change in snow/ice cover is simply the difference between formation and melting. Also calculated were the number of grid points where there was snow/ice cover in the UM but not in the IMS and vice-versa. Figure 12 and figure 13 compare the snow coverage for IMS data in UM coordinates and the UM data for two date ranges. September 2002 is shown on both figures. The UM statistics displayed are, of course, for the Northern Hemisphere only. From the total snow cover plot, it can be seen that the UM snow cover seems to form slightly in advance of the IMS at the start of winter 2002/2003. In January and February the total UM snow cover is slightly less than the IMS for 2002 but pretty similar in 2003. The UM snow cover melts far too rapidly in both spring 2002 and 2003. It can also be stated that the UM snow cover is more variable than the IMS data (i.e. more points melt and form on a typical day), this could be wholly or partly due to the IMS being formed from more than one day's data making it less sensitive to short time-scale variations. It could also be asserted that the IMS data normally changes quite slowly but is punctuated by sudden changes (the melting and formation plots are generally quite low but contain large spikes) although this is less apparent.

Figures 14 and 15 are the sea-ice analogs of figures 12 and 13. The amount of sea-ice cover in the UM is almost universally less than the sea-ice cover in the IMS although there is reasonable agreement both in May 2002 and 2003. From the bottom plot, it can be seen that the number of points where there is sea-ice in the IMS only is far greater than the number of points where there is sea-ice in the UM

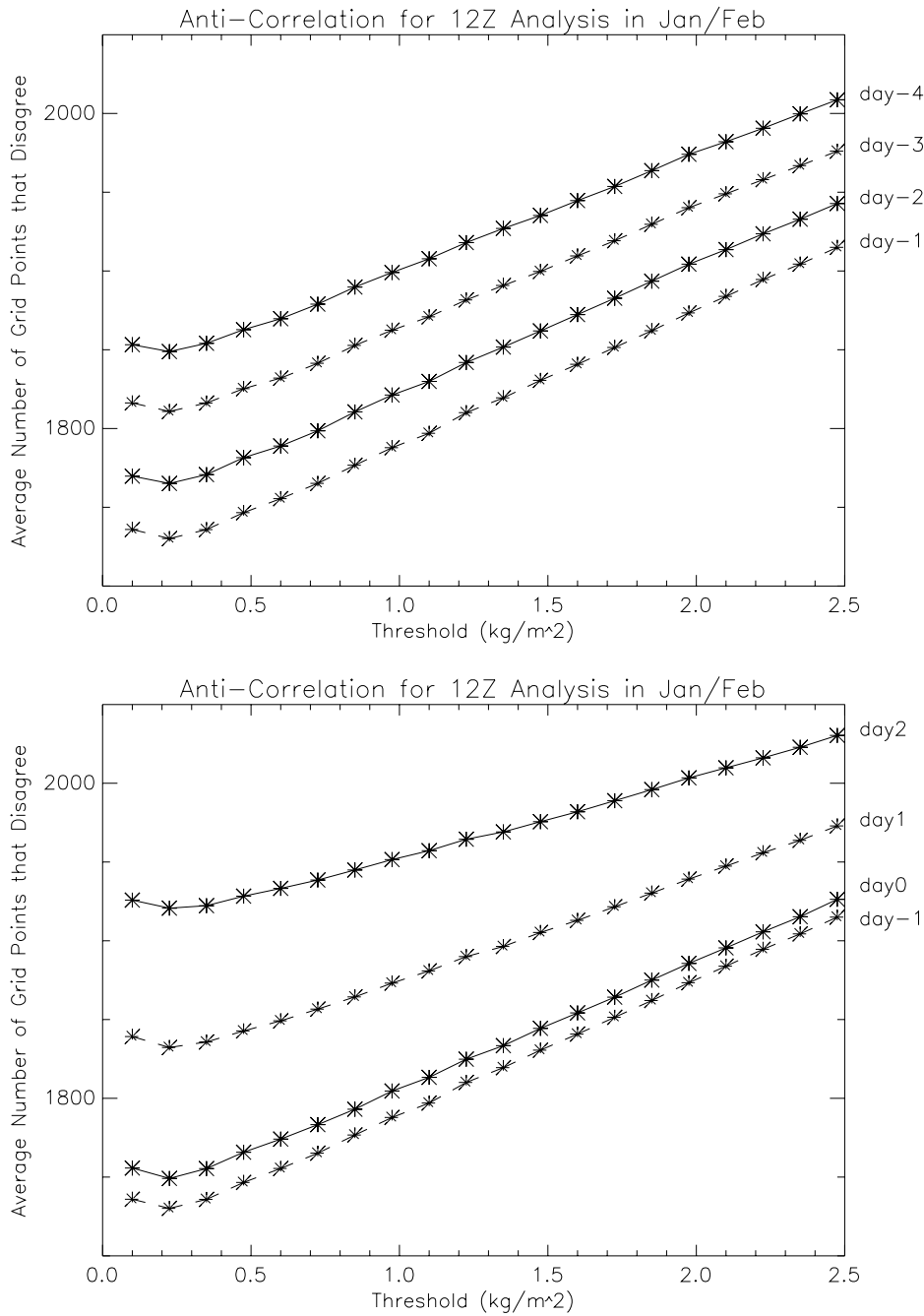


Figure 8: The degree of correlation between IMS snow cover and 12Z UM analyses for various days against snow threshold in January/February.

only. This all suggests that we would like to reduce the sea-ice fraction threshold for the comparison—which will have no effect as it is already below the minimum fraction that occurs. Under representing the extent of sea-ice cover in the model will have implications for satellite data assimilation because sea ice has a substantial impact on the measured radiances. Any attempt to cut satellite observations with sea ice in the field of view will probably use the model background together with other criteria, for example ATOVS processing uses the model background, AMSU radiances and crude geographical cut-offs. The spike in UM sea-ice cover in August is

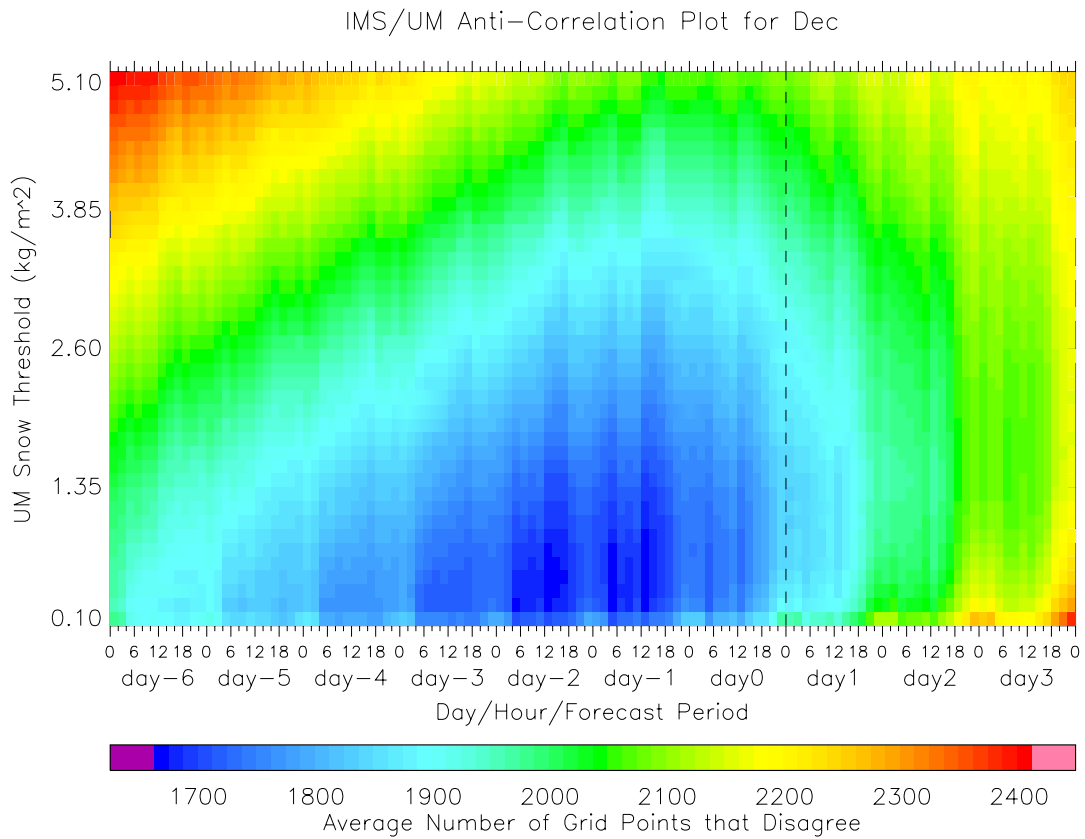


Figure 9: The degree of correlation between an IMS file and contemporary UM snow fields for different snow thresholds in December.

due to the introduction of new dynamics. There are five other spikes, however, where the sea-ice cover dramatically increases and then, soon after, reverts to the previous trend. These are due to the sea-ice cover briefly switching to the climatological default, see [8]. The dates when climatological sea-ice was used were 20th March 2002, 6th/7th January 2003, 27th February to 4th March 2003 inclusive, 27th May 2003 and 14th July 2003. The top two maps in figure 16 show the UM sea-ice fields for the 5th and 6th January 2003. All the cases of climatological sea-ice are all preceded by a repeated sea-ice field. There are a total of 31 repeated sea-ice fields during the period studied and no examples of a field being repeated more than once. The sea-ice fields are supplied by NCEP and should there be an ftp outage, or some other problem, then the previous day's sea-ice field is carried forward but should the outage last more than one day then the climatological default is used. This behaviour was due to a bug which has now been fixed and sea-ice fields will now be carried over for up to a week in the event of an outage.

Another peculiarity of the sea-ice field is visible in the top map of figure 16, there is a stripe of thin ice north of Russia. Stripes like these have been seen for a wide range of dates and sometimes have no ice at all, for example the third map in figure 16. These holes are most common when the sea-ice cover is at its minimum, around September, but the date range where thin patches appear is less well studied. These stripes all tend to appear along the same latitude: 86.11° , 86.66° , 87.22° and 87.78° with 87.22° being the most common. No SSM/I based sea-ice product gives directly observed sea-ice concentrations within about 3° of the pole because of the

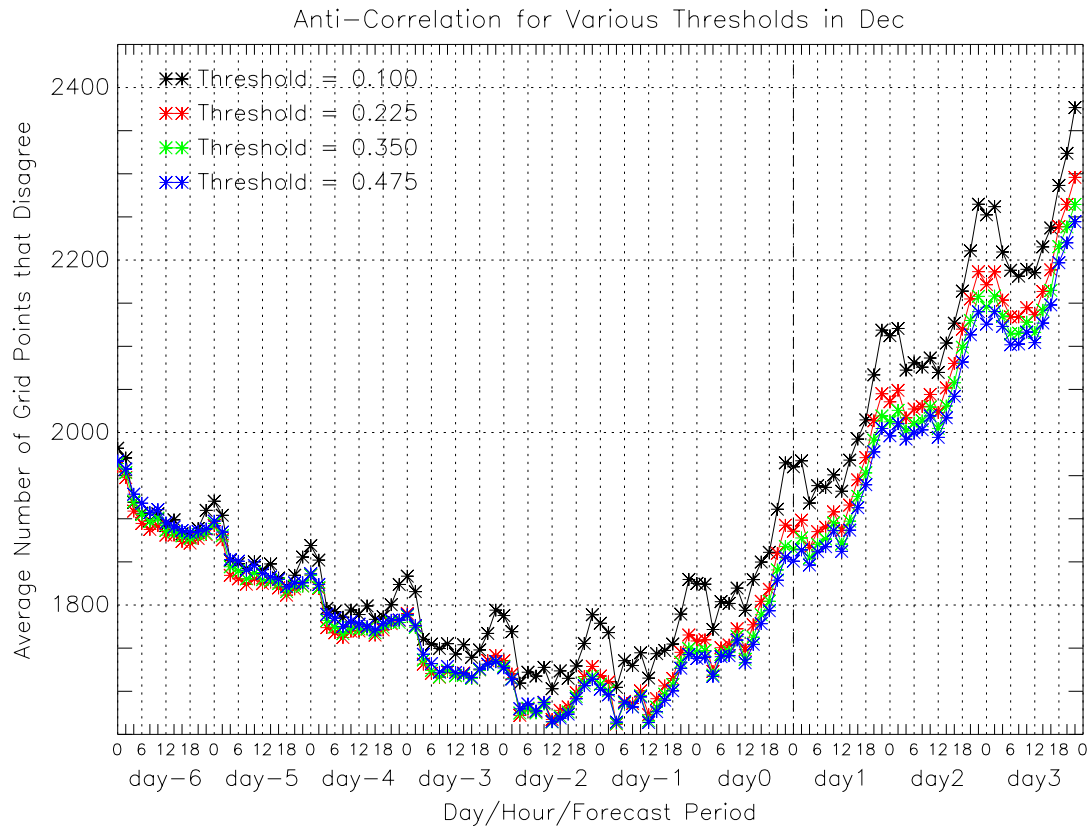


Figure 10: The degree of correlation between an IMS file and contemporary UM snow fields for different snow thresholds in December.

orbital path. It therefore seems likely that the holes and thin sea-ice patches are due to missing satellite data with the area closest to the pole being set to some default value. How missing data is treated in the production of the sea-ice field should be investigated.

The statistics were also broken down into four regions, loosely named: North America, Europe, the Middle East and the Far East. North America was defined as all (northern hemisphere) points between -170° and -60° longitude, Europe was defined as lying between -10° and 30° , the Middle East was defined as 30° to 65° and the Far East as 65° to -170° . Figures 17 and 18 show the total snow coverage for UM and IMS data for each of these regions while figures 19 and 20 show the number of grid points which appear in the UM but not the IMS and the number of grid points that appear in the IMS but not the UM for each region. With the exception of the Middle East, the snow cover forms slightly more quickly in the UM than in the IMS at the start of winter. In the spring, the UM snow cover melts far too quickly in all regions. The total UM snow cover in the Far East is greater than the IMS snow cover for most of the 2002/2003 winter period.

Figures 21 to 26 show map frequency histograms, for various time intervals, of the fraction of days where the UM and IMS data sets agree there is snow/ice coverage, the fraction of days the IMS data has snow/ice cover but the UM does not and the fraction of days the UM has snow/ice cover but the IMS data does not. Comparing figure 21 with figure 25 it can be seen that the excess of snow in the Far East is far less apparent for early 2002 than 2003. The tendency for the IMS to have

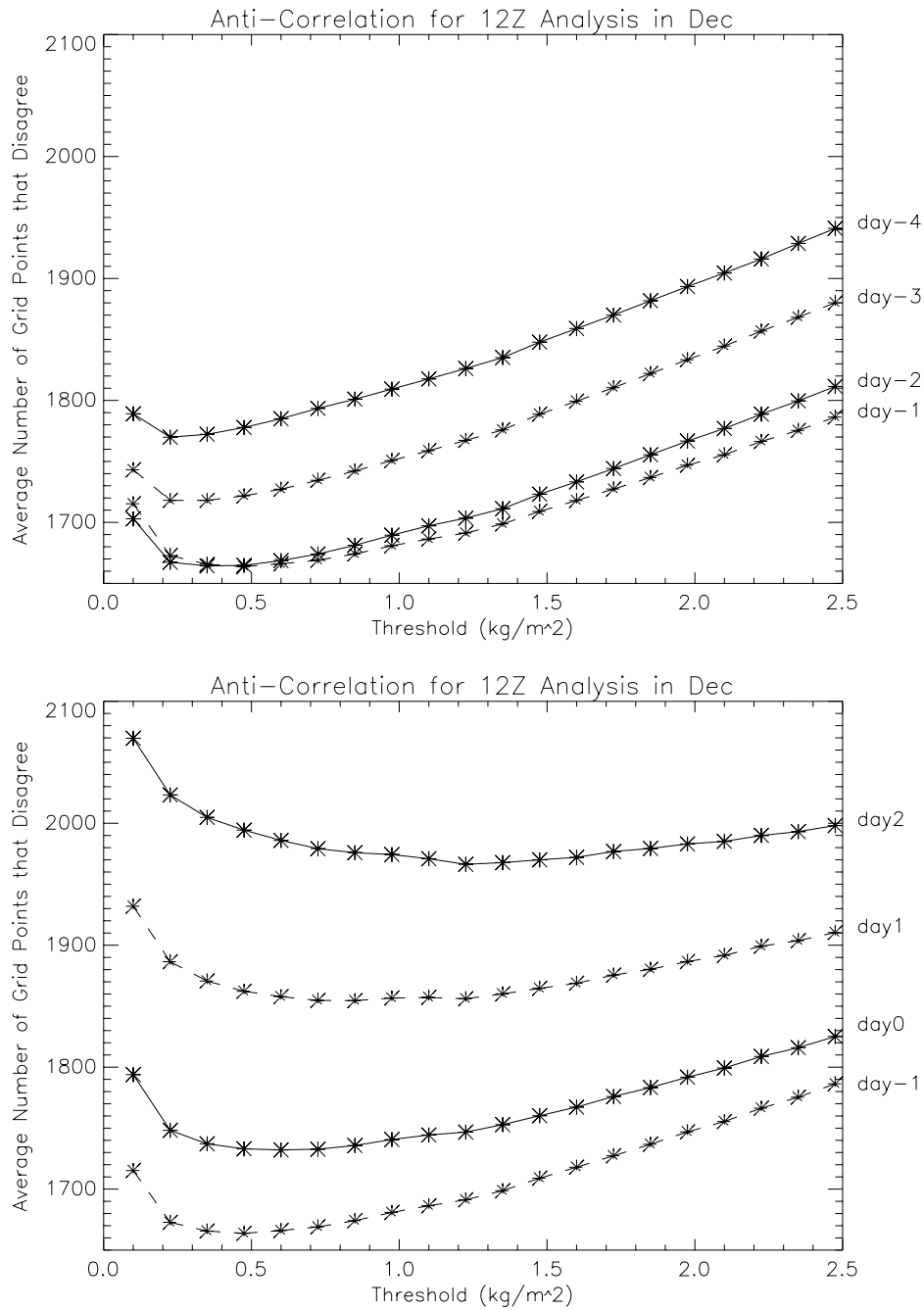


Figure 11: The degree of correlation between an IMS file and 12Z UM analysis snow fields for different snow thresholds in December.

more snow cover in the USA, Europe and north of the Caspian Sea is present in both plots. Similar conclusions can be drawn from a comparison of March 2002 to March 2003. In June/July/August 2002 the IMS has more snow cover in northern Canada and more sea-ice. In September/October/November 2002, the anomalous holes in the UM sea ice are prevalent in the middle plot and the excess of UM snow in the Far East can be seen in the bottom plot.

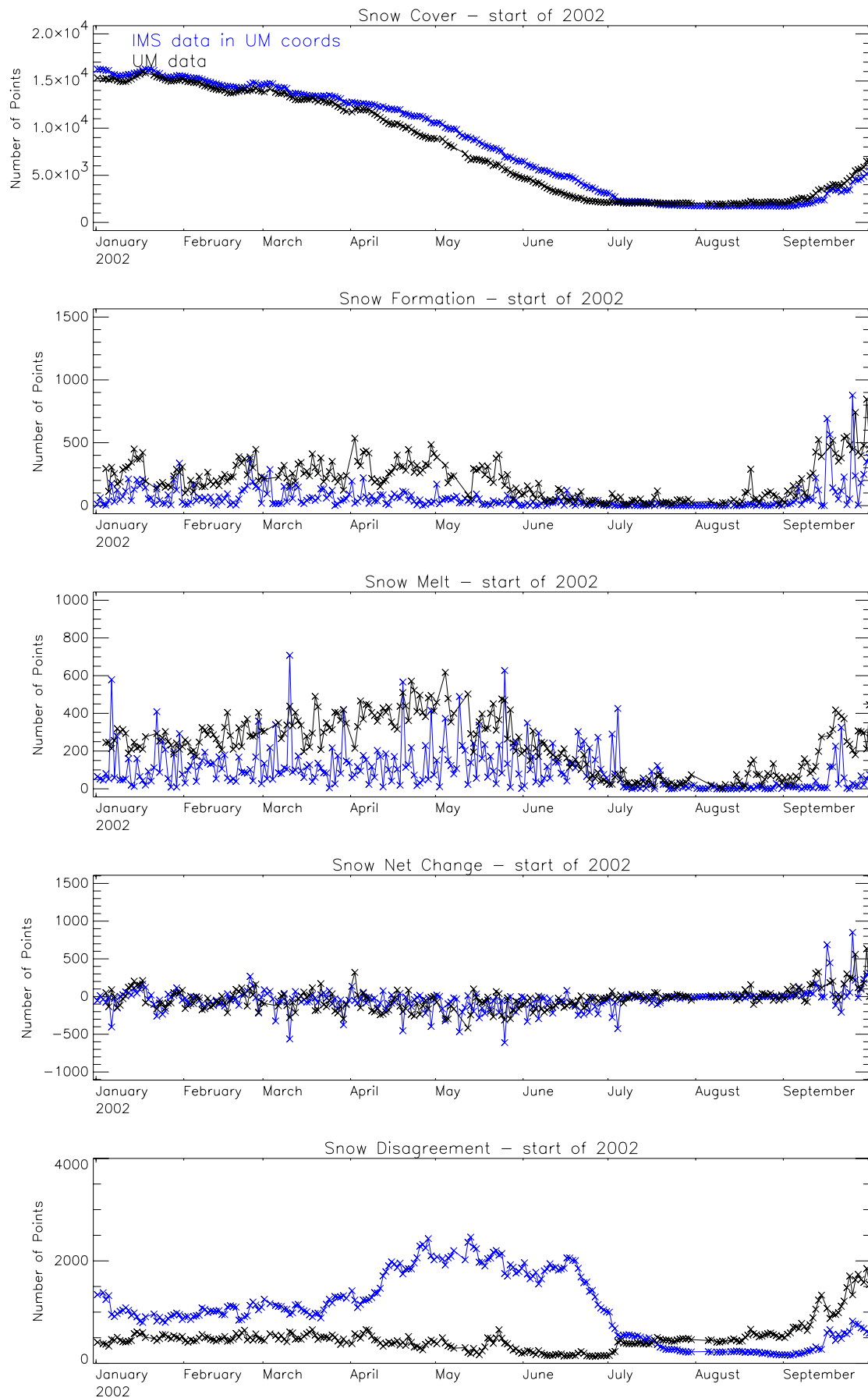


Figure 12: Comparison of IMS and UM snow cover. The bottom plot shows the number of grid points that are snow covered in the UM but not in the IMS and vice-versa.

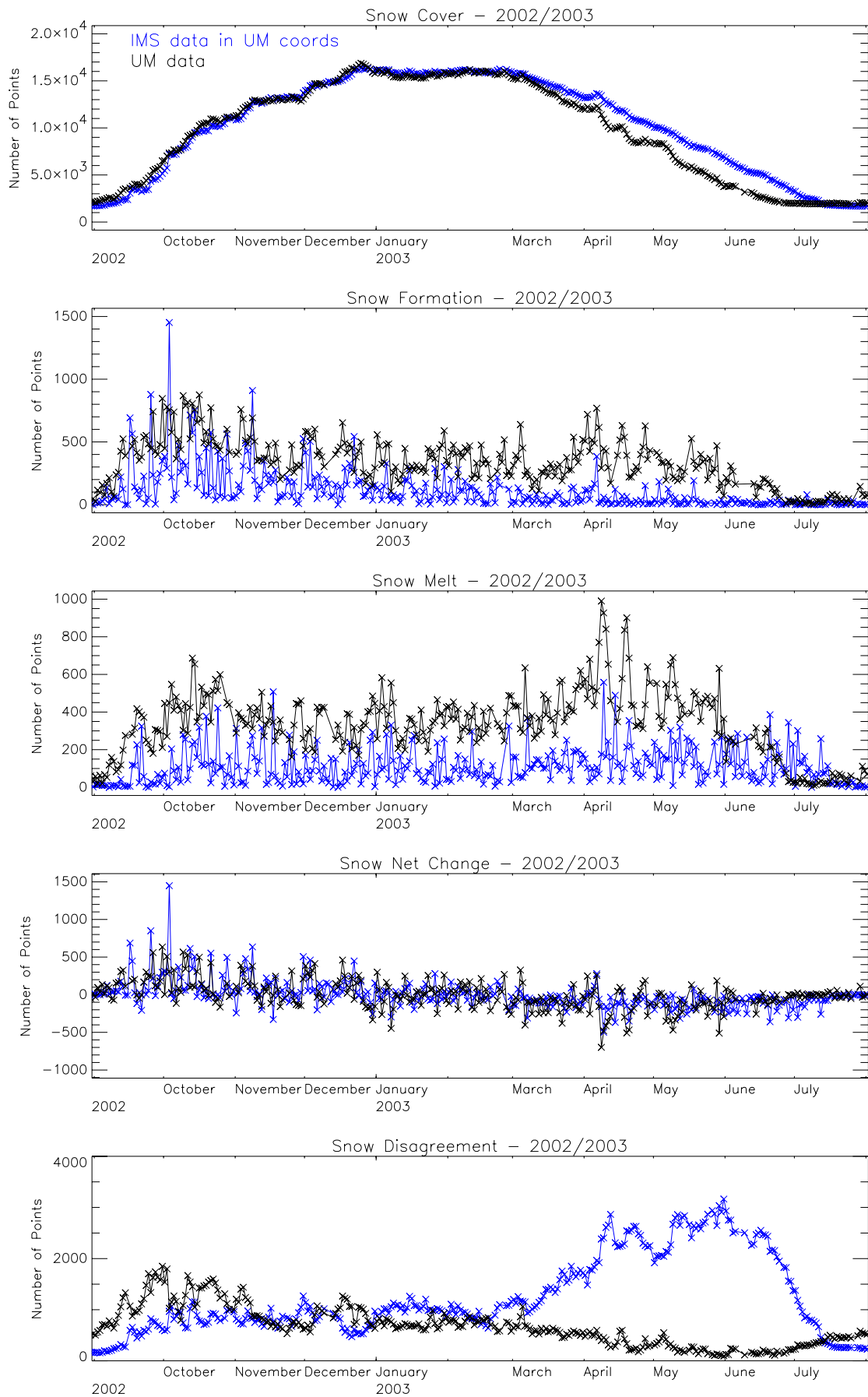


Figure 13: Comparison of IMS and UM snow cover. The bottom plot shows the number of grid points that are snow covered in the UM but not in the IMS and vice-versa.

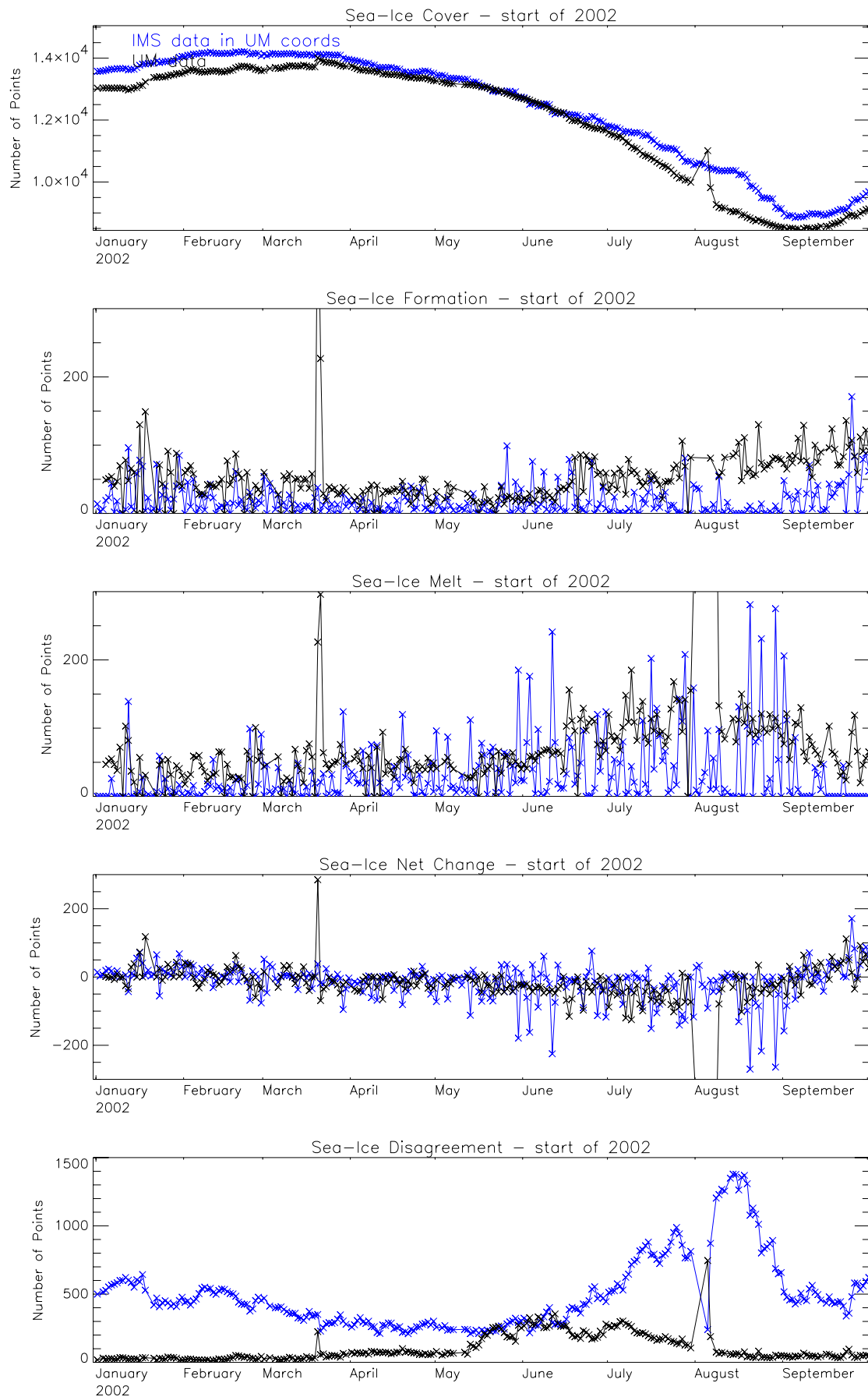


Figure 14: Comparison of IMS and UM sea ice cover. The bottom plot shows the number of grid points that are ice covered in the UM but not in the IMS and vice-versa.

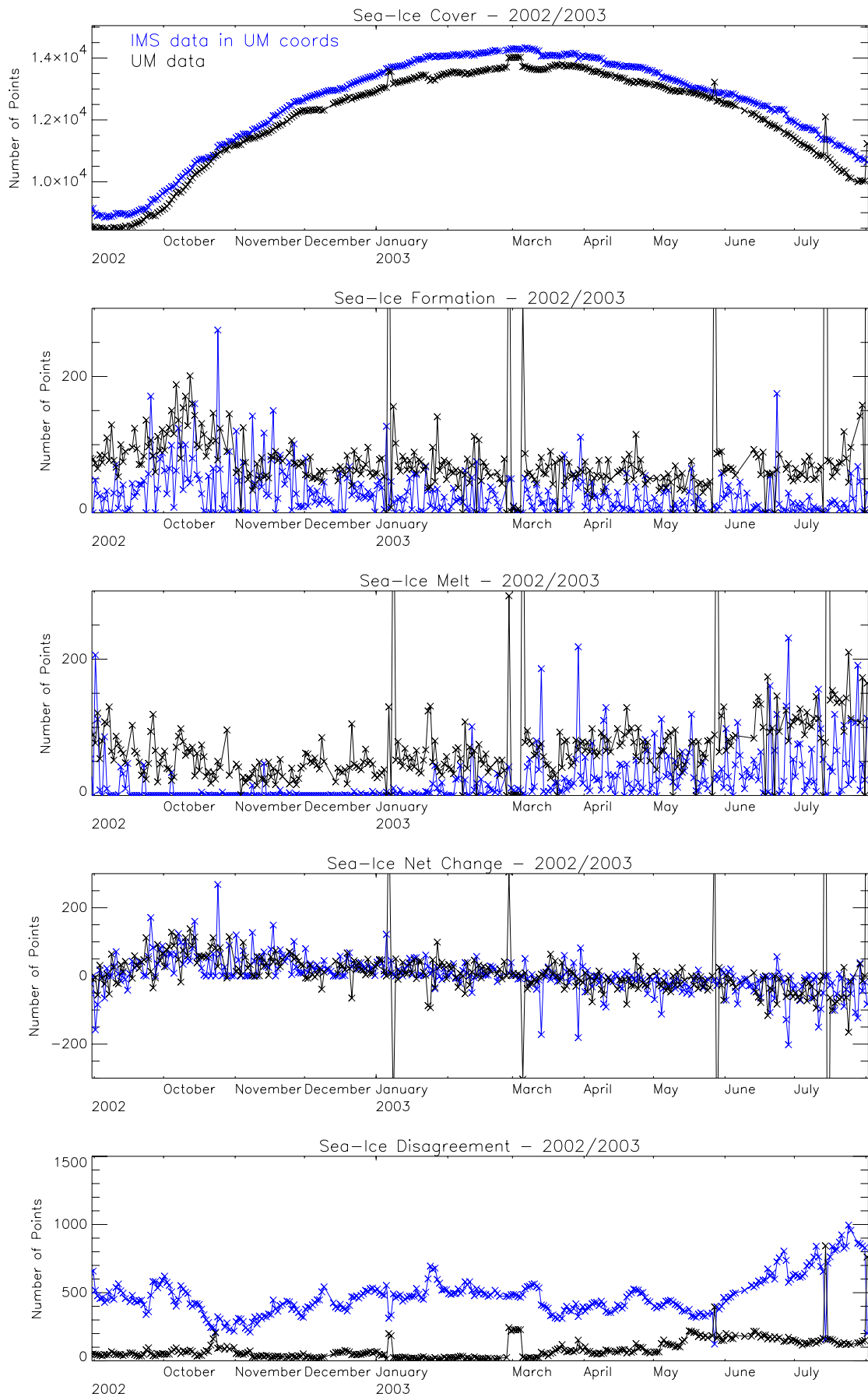


Figure 15: Comparison of IMS and UM sea ice cover. The bottom plot shows the number of grid points that are ice covered in the UM but not in the IMS and vice-versa.

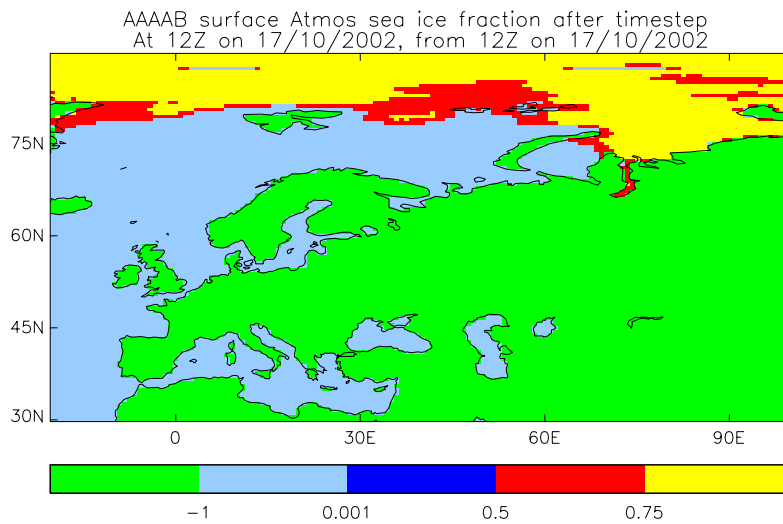
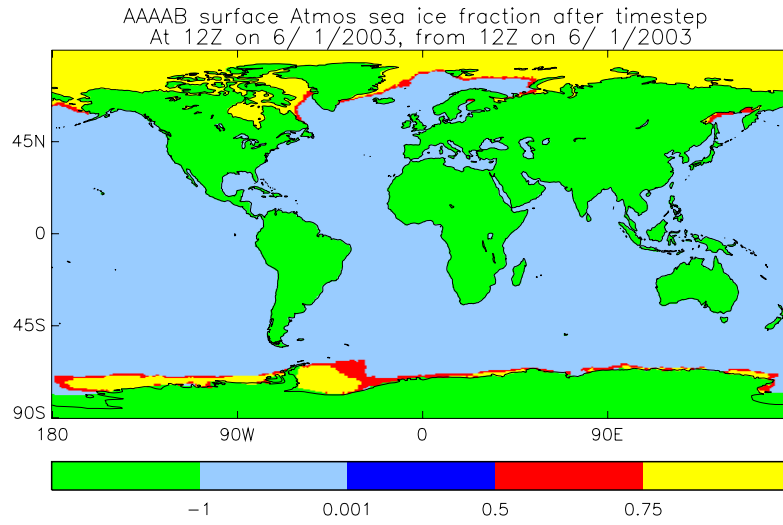
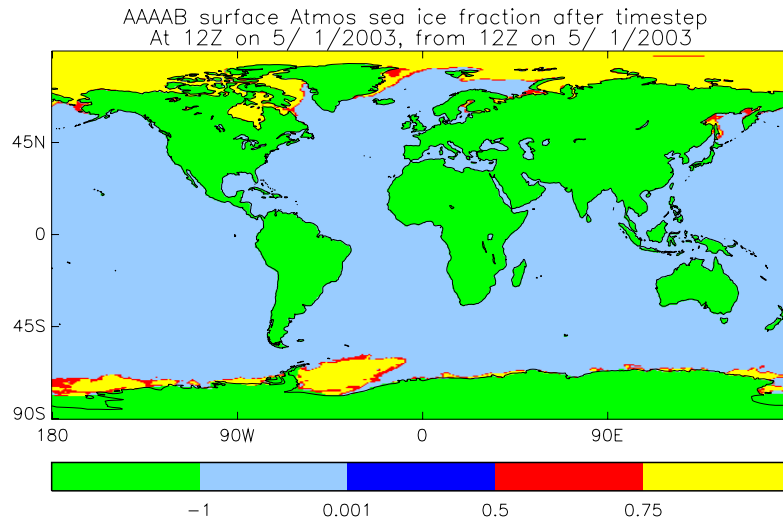


Figure 16: UM sea-ice fraction for 05/01/2003, 06/01/2003 and 17/10/2002. The sea-ice fraction for 06/01/2003 is the climatological sea-ice field. The sea-ice fraction for 17/10/2002 demonstrates that some of the ice fields contain unnatural-looking holes in the polar ice cap.

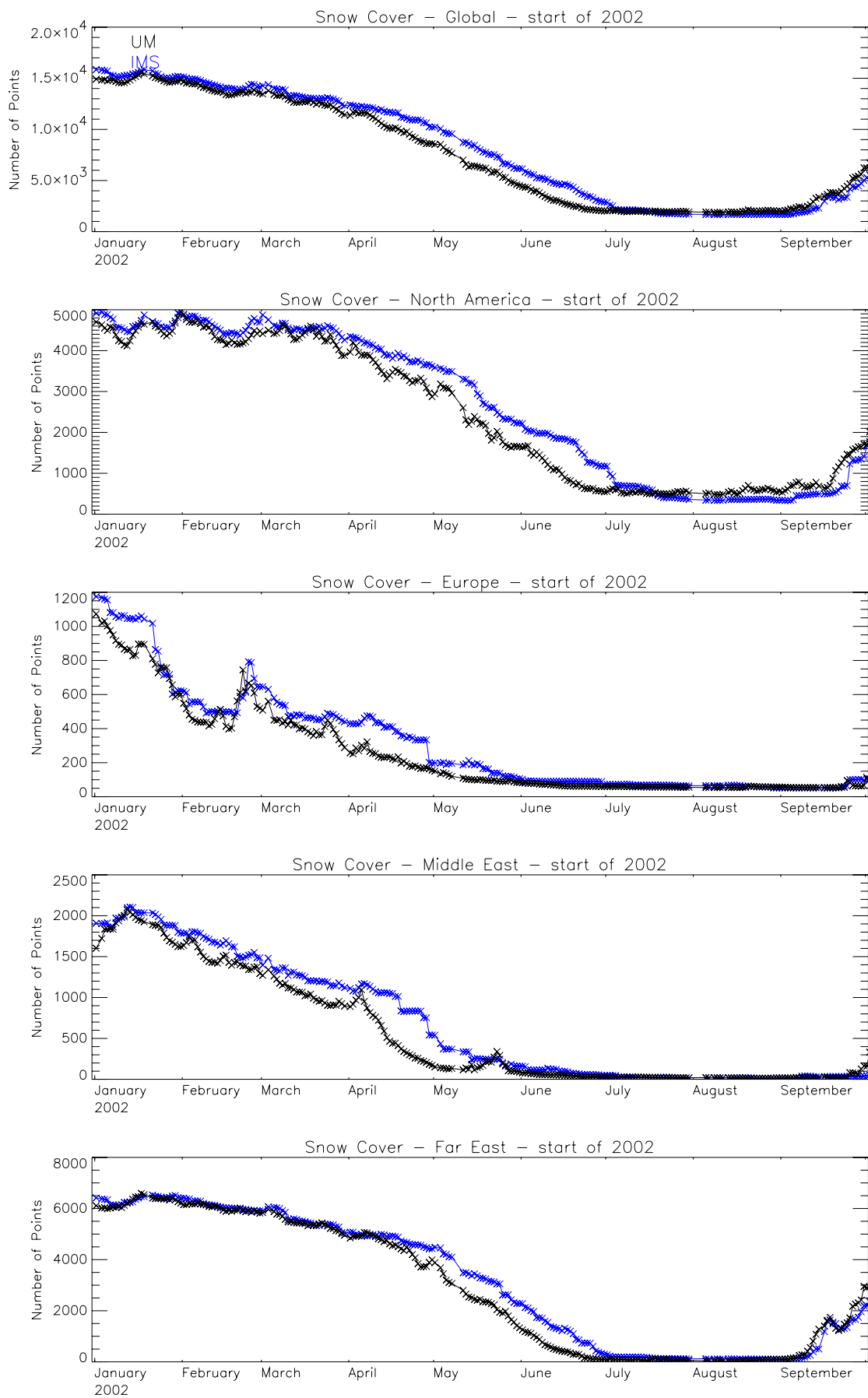


Figure 17: Total snow cover in the UM and IMS for various regions.

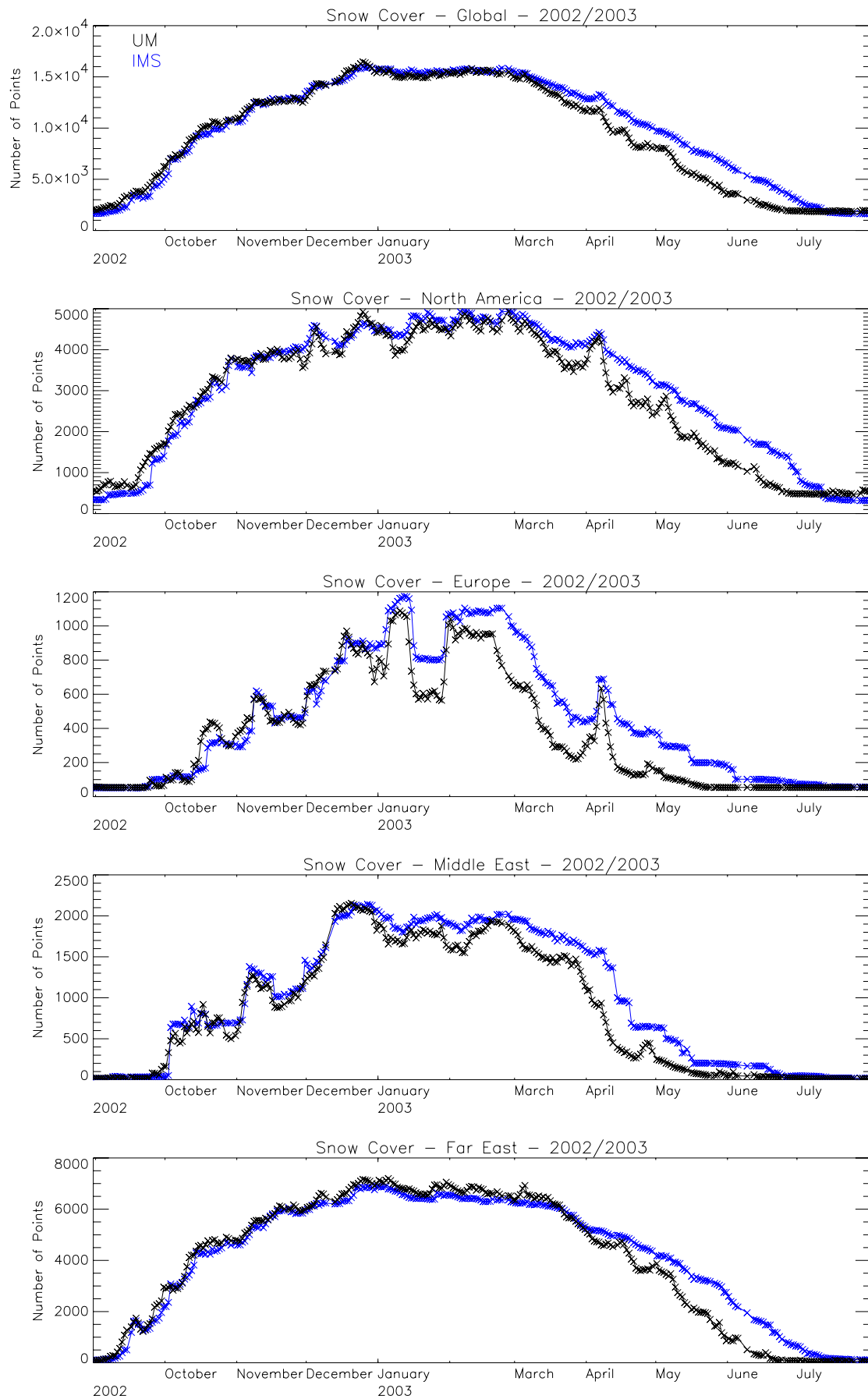


Figure 18: Total snow cover in the UM and IMS for various regions.

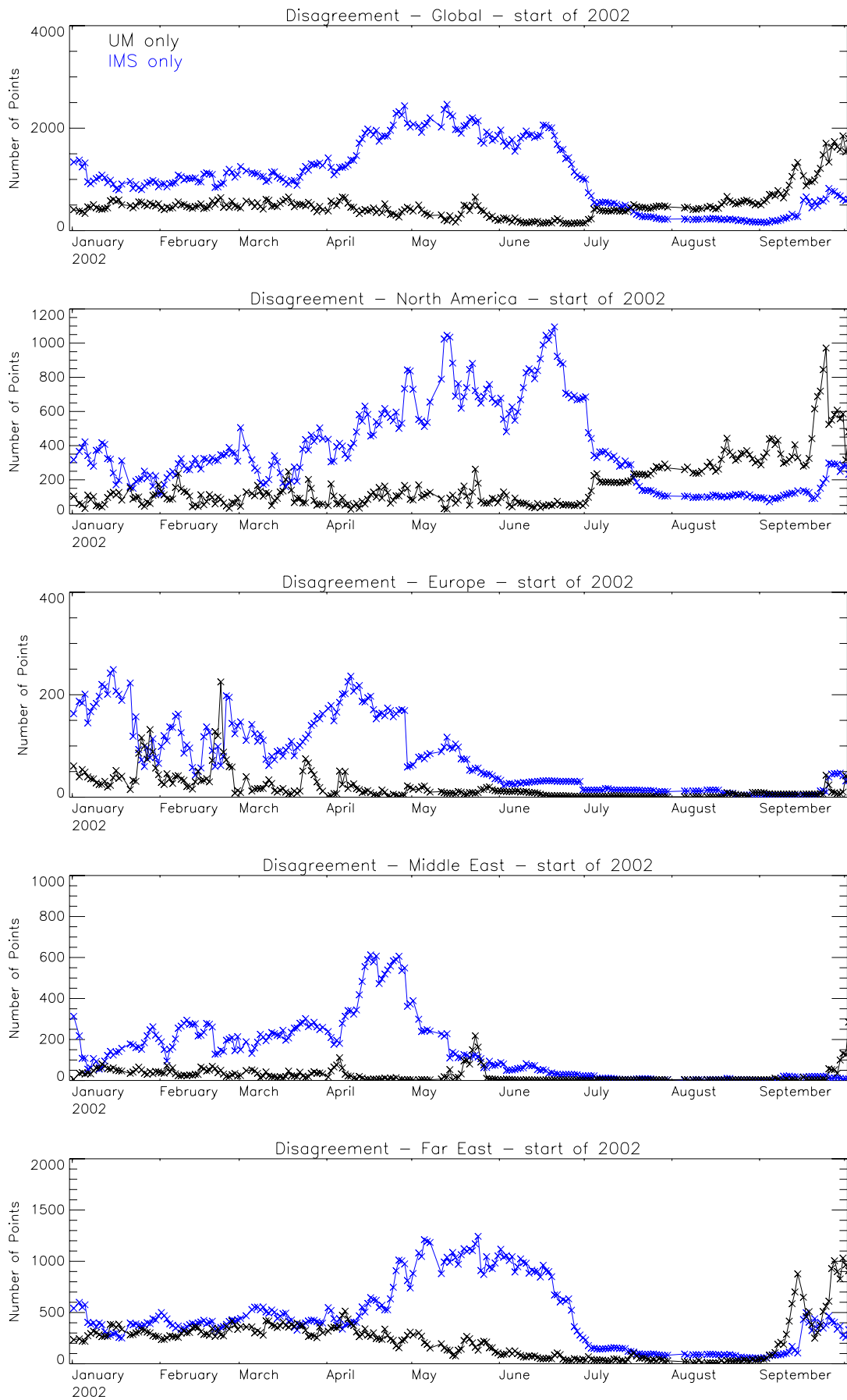


Figure 19: The number of grid points where there is snow cover in the UM but not in the IMS and vice-versa.

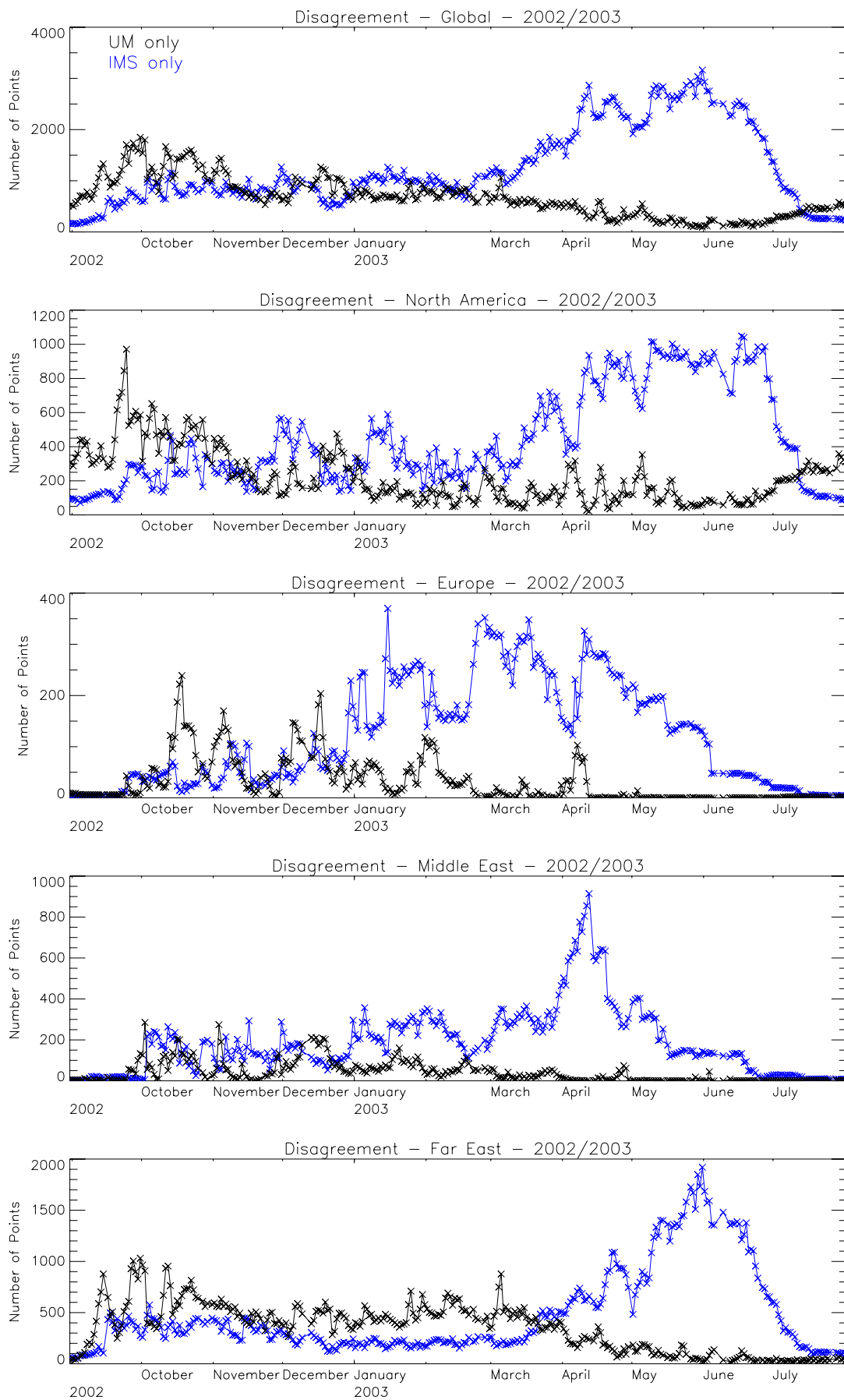
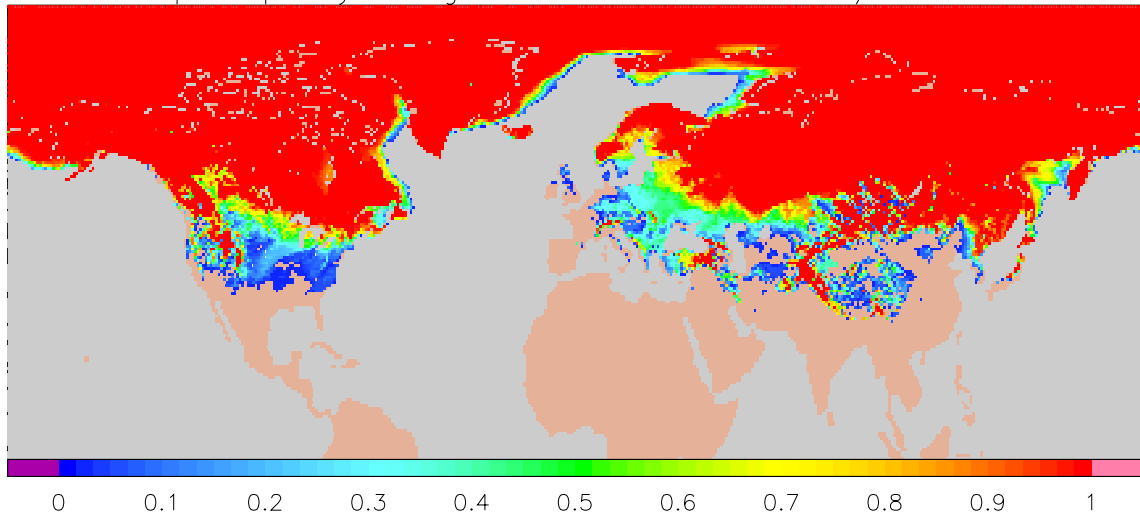
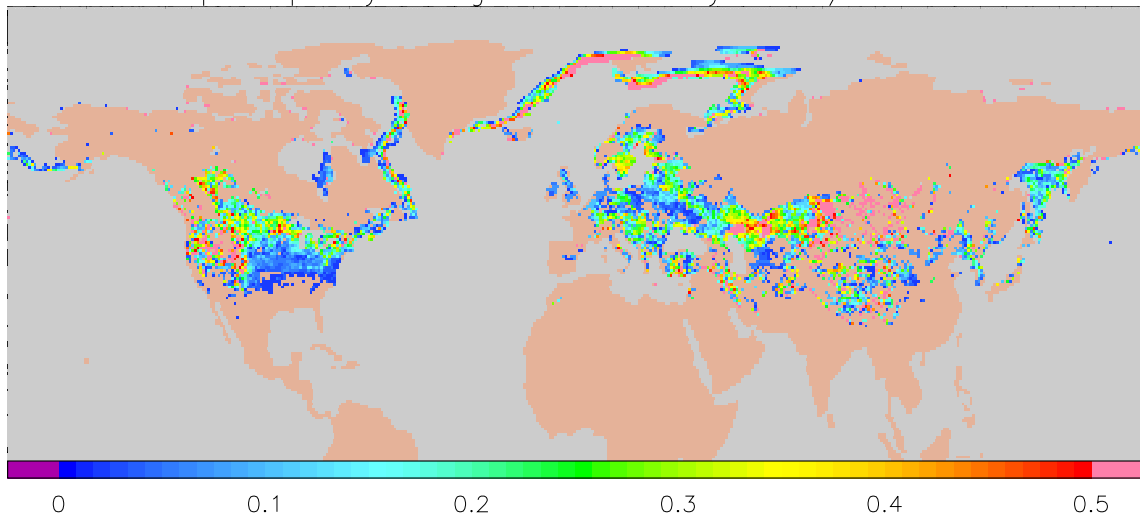


Figure 20: The number of grid points where there is snow cover in the UM but not in the IMS and vice-versa.

Map Frequency Histogram of UM and IMS – Jan/Feb 2002



Map Frequency Histogram of IMS only – Jan/Feb 2002



Map Frequency Histogram of UM only – Jan/Feb 2002

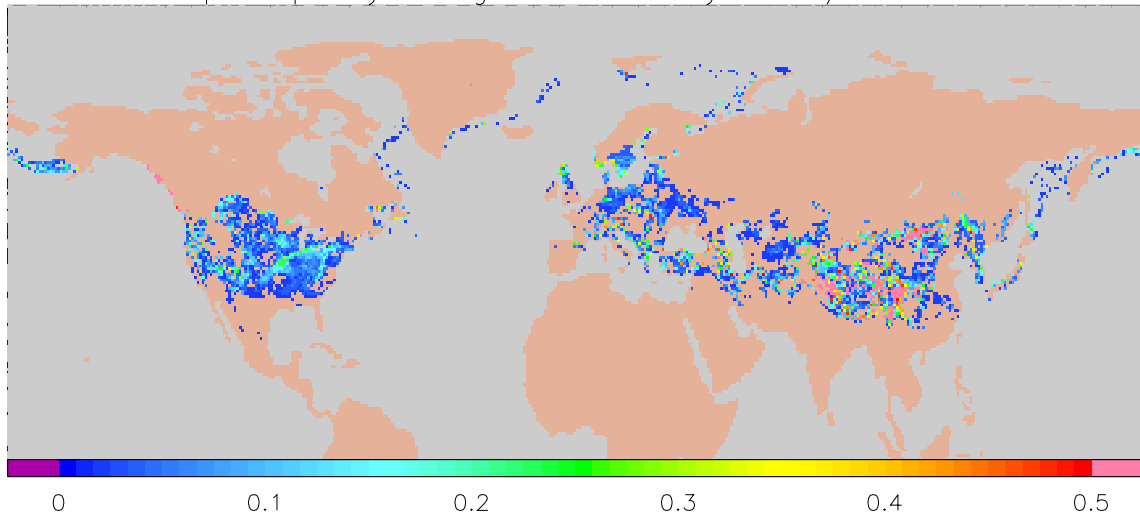
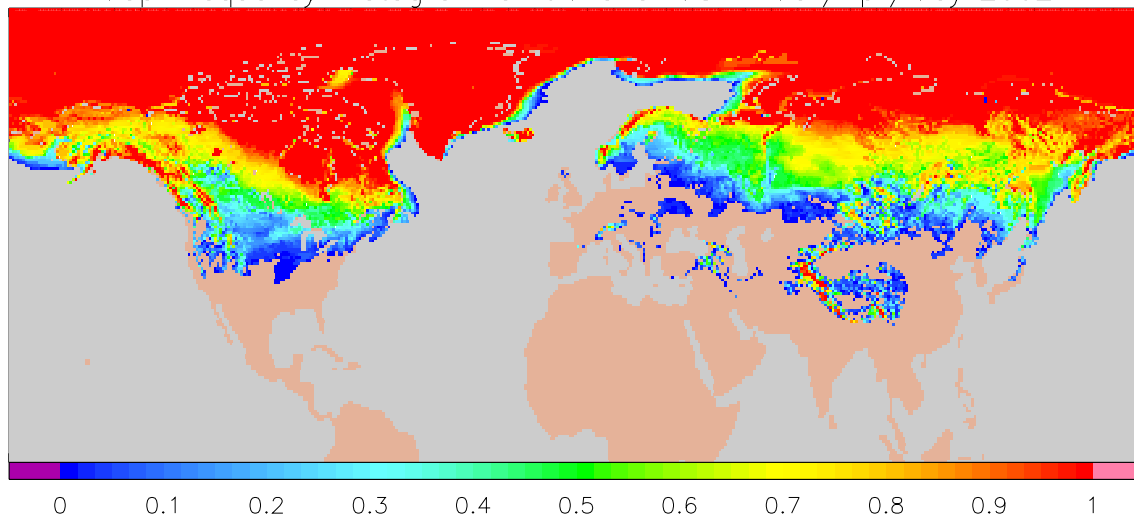
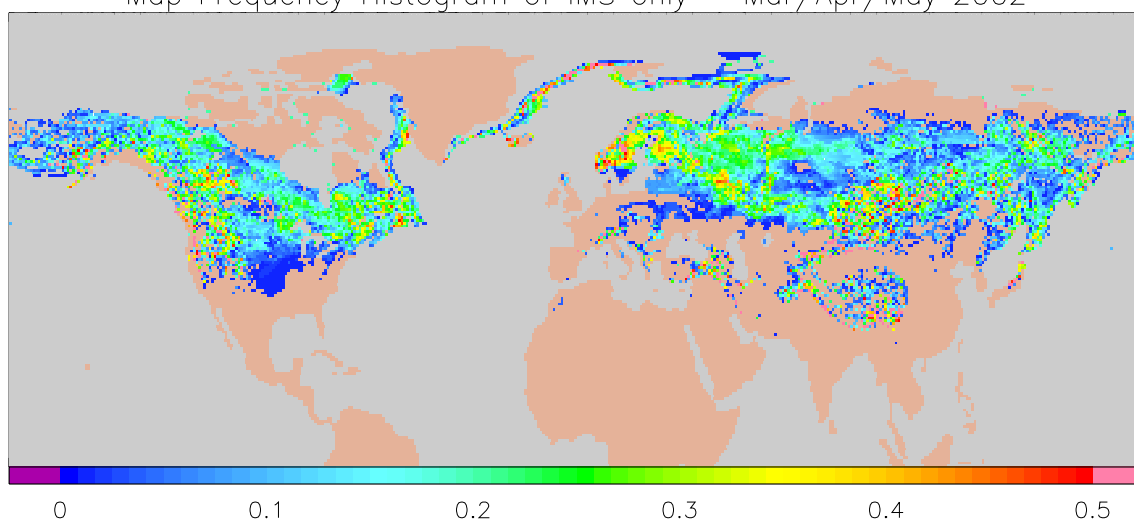


Figure 21: Jan/Feb 2002, see the text for details.

Map Frequency Histogram of UM and IMS – Mar/Apr/May 2002



Map Frequency Histogram of IMS only – Mar/Apr/May 2002



Map Frequency Histogram of UM only – Mar/Apr/May 2002

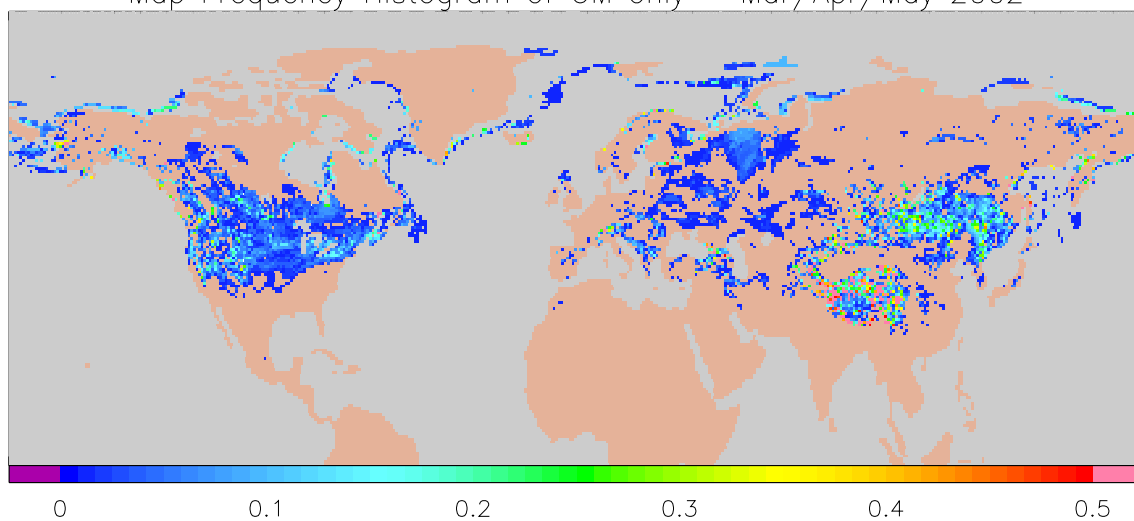


Figure 22: March 2002, see the text for details.

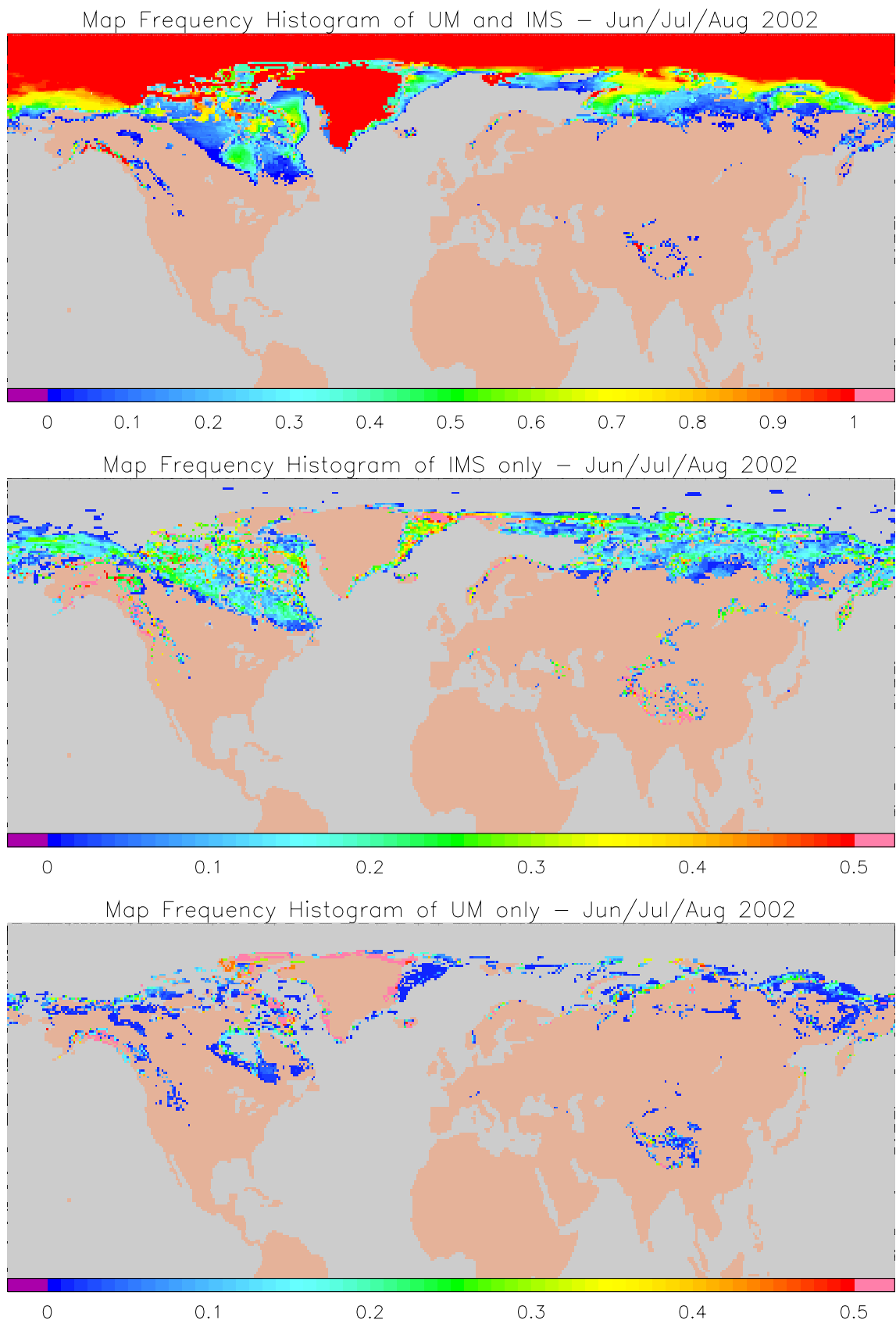


Figure 23: Jun/Jul/Aug 2002, see the text for details.

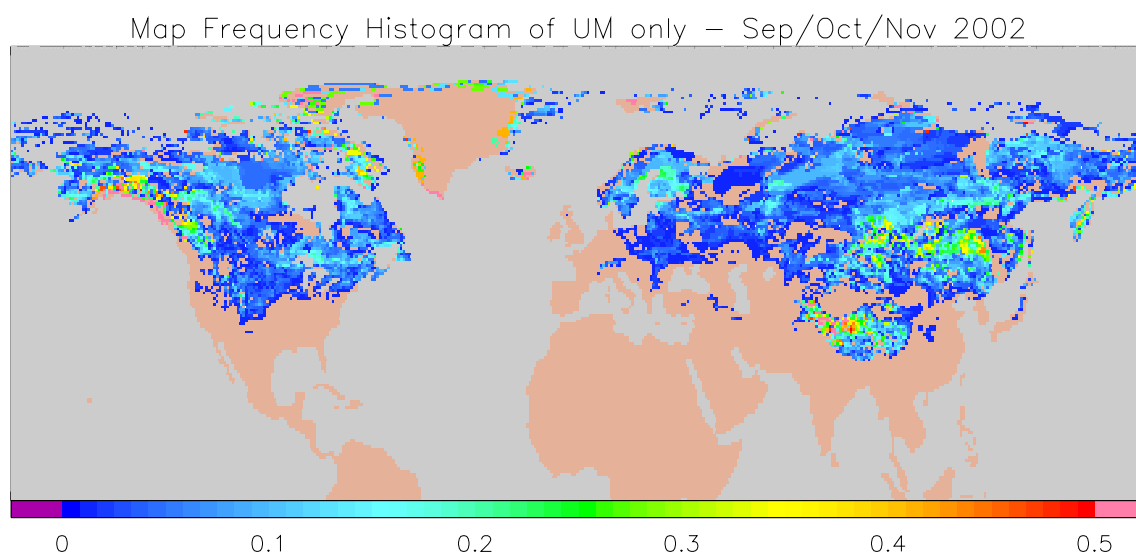
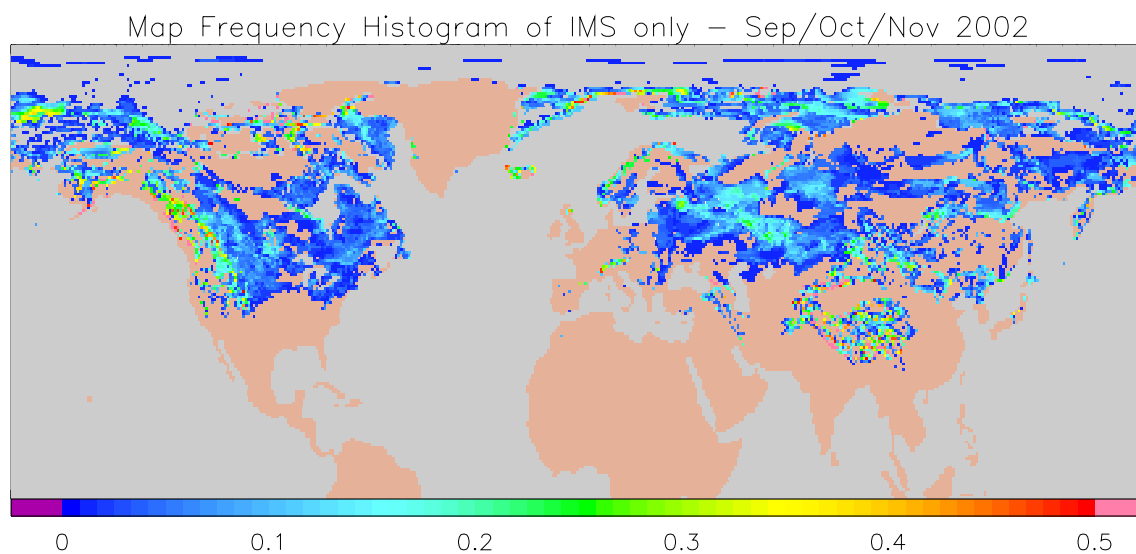
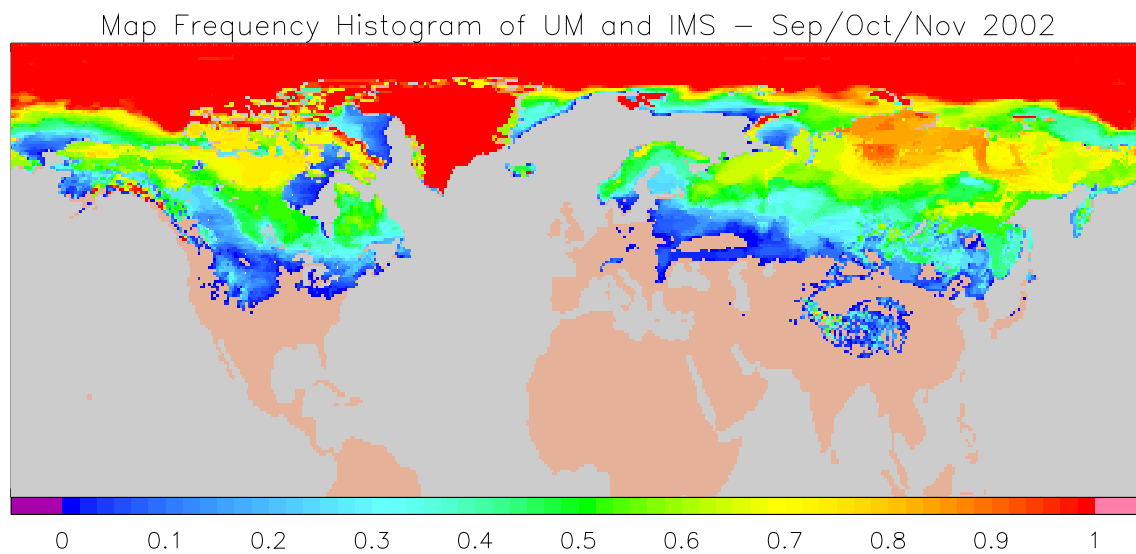
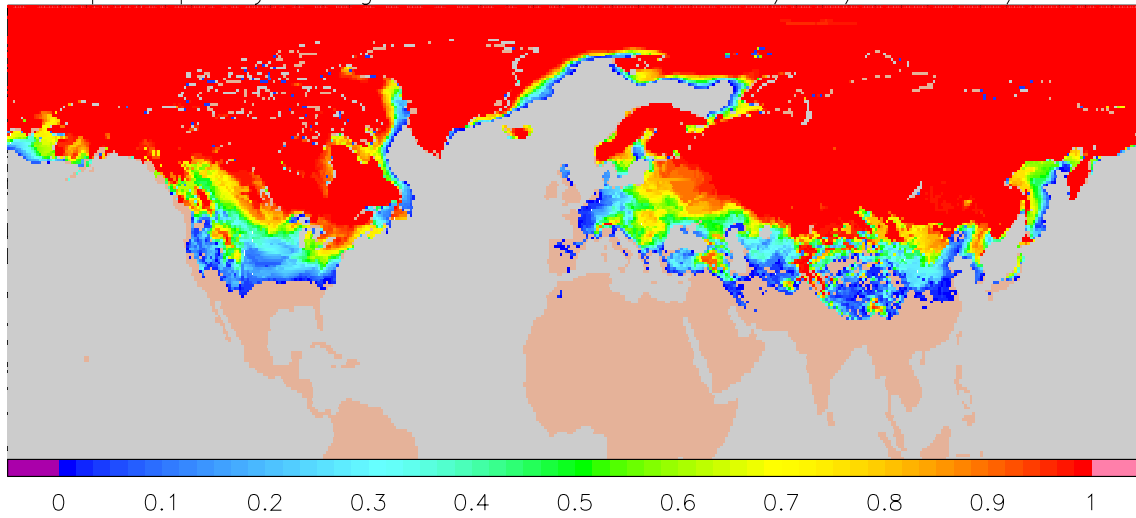
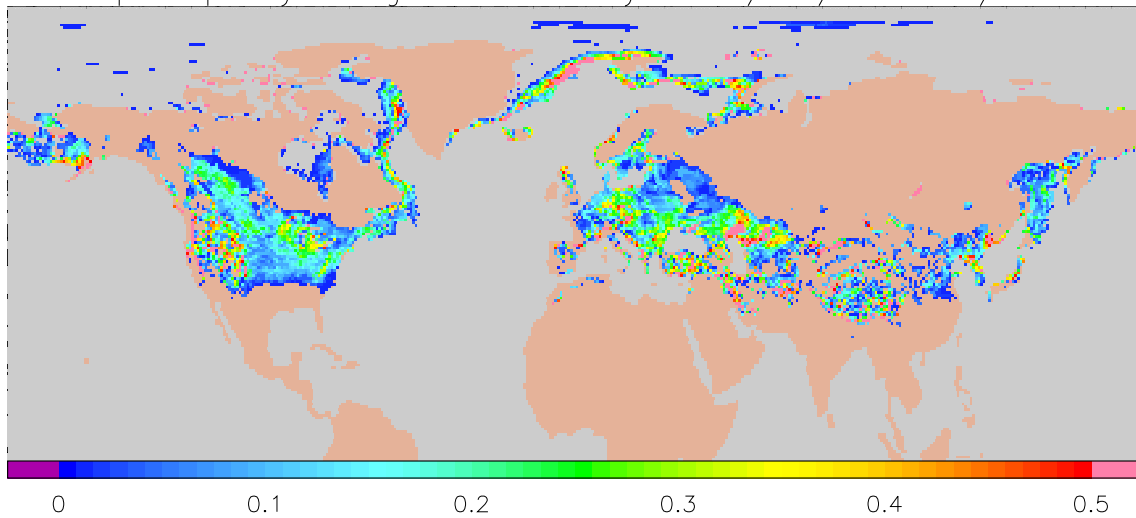


Figure 24: Sep/Oct/Nov 2002, see the text for details.

Map Frequency Histogram of UM and IMS – Dec/Jan/Feb 2002/2003



Map Frequency Histogram of IMS only – Dec/Jan/Feb 2002/2003



Map Frequency Histogram of UM only – Dec/Jan/Feb 2002/2003

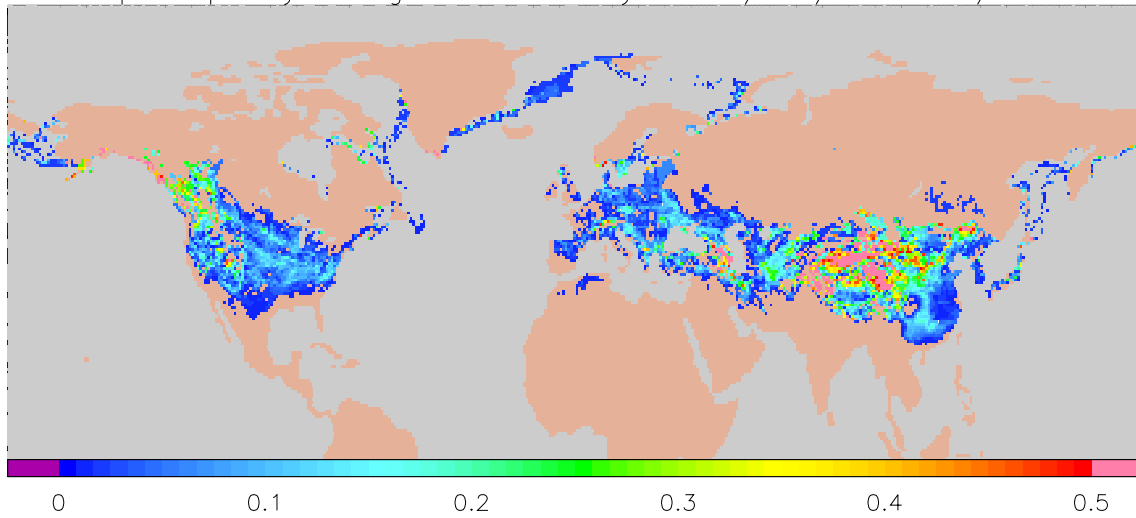


Figure 25: Dec/Jan/Feb 2002/2003, see the text for details.

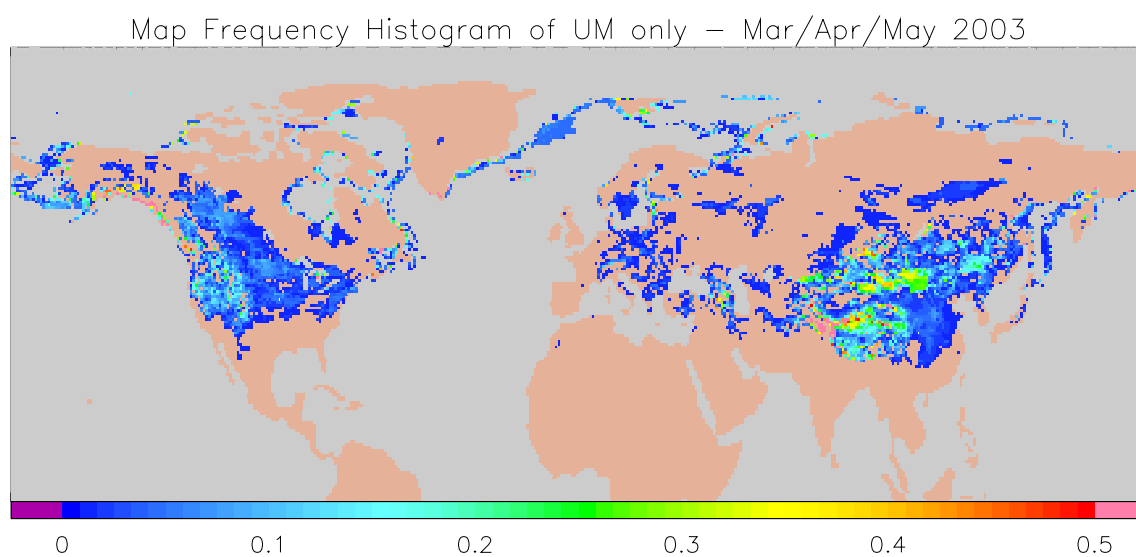
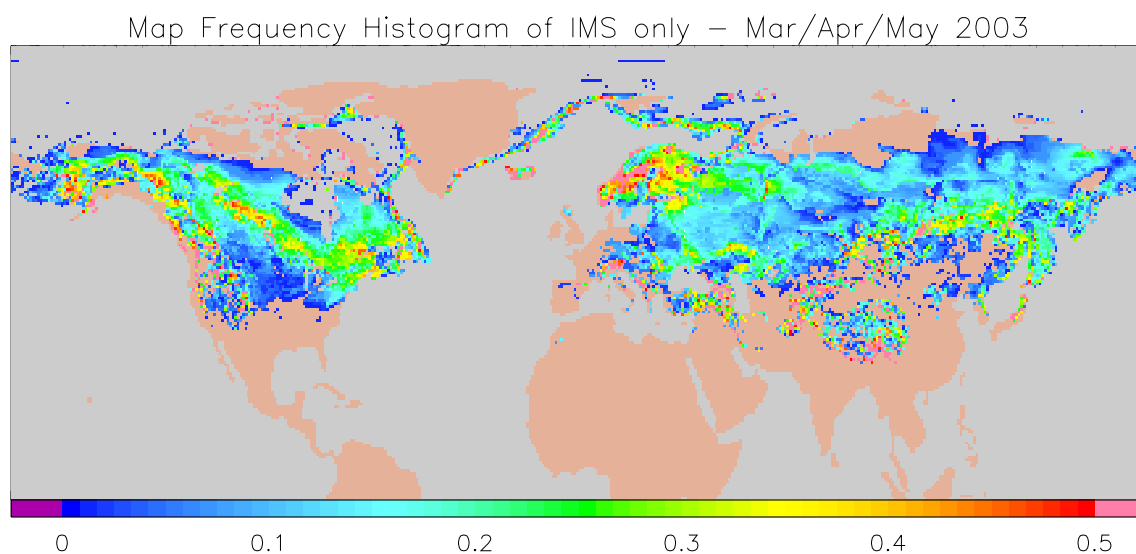
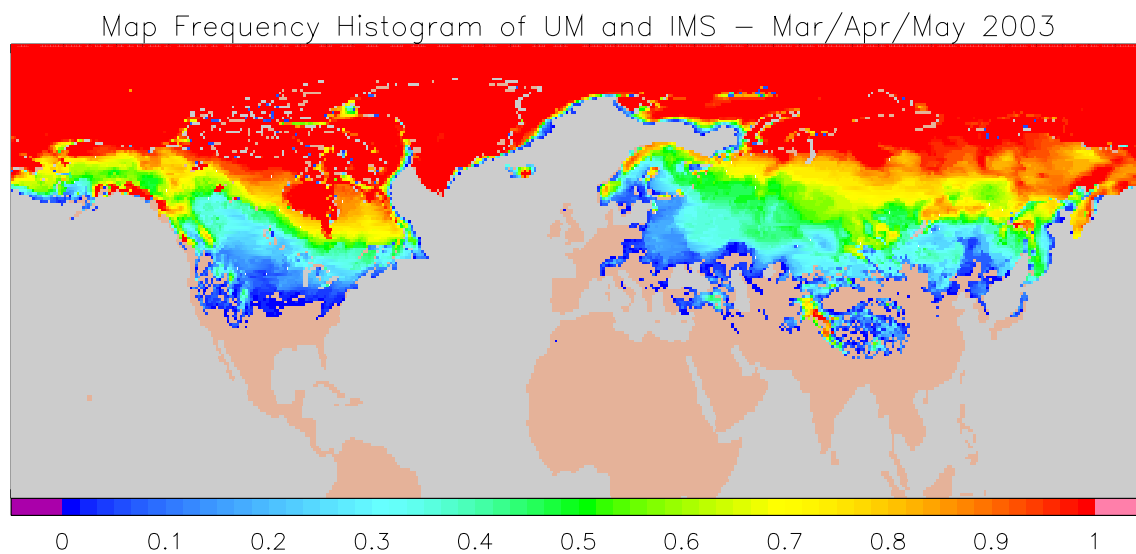


Figure 26: March 2003, see the text for details.

4 Comparison with USAF Snow Depth Data

4.1 USAF Snow Depth Data

USAF northern hemisphere snow cover and sea-ice analysis (USAF) is available in both grib and binary formats from the NCEP ftp server, in the same directory as the IMS data. USAF snow depth is one of the inputs used to generate the IMS map. Clearly snow depth is an important parameter both from the point of view of verification and assimilation, so it was decided to use the USAF data for a brief comparison.

A paper describing the method used to generate the snow depth analysis [9] states that a map is produced for both hemispheres, although the data file on the NCEP server only contains the Northern Hemisphere. The USAF snow analysis uses snow depth reports from around the world as its primary data source. Station observations do not always include a snow depth measurement even when snow is present, so observations without a snow measurement are only counted as zero depth if the temperature exceeds a certain value or the state of the ground indicates no snow cover. If there is a significant difference between the altitude of the observation and the grid point, then the depth is either adjusted or discarded. The snow depth assigned to each grid point is an inverse-distance weighted combination of up to the 5 nearest observations within 250 km. Where there are no observations within 250 km, SSM/I measurements are used to determine if there is snow cover. The SSM/I algorithm is designed to err on the side of no snow, so SSM/I measurements are only allowed to increase snow cover. Where the SSM/I algorithm detects new areas of snow, the snow depth is set to four inches and thereafter the depth is trended towards climatology. Any grid points without nearby observations or SSM/I measurements are also trended towards climatology but climatology is only allowed to add snow to grid points where snow already exists. The USAF analysis also includes the presence or absence of sea-ice. Sea-ice is considered to be present if an SSM/I based ice algorithm indicates a concentration of 15% or more.

The format of the USAF data file on the NCEP ftp server is described in a README file [10]. The USAF data is updated daily at 00:11 UTC. The earliest USAF data ftp'd over was for the 6th January 2003 but there are large gaps from 23rd February to the 3rd March and from the 3rd March to the 10th March when there were ftp problems. The binary file consists of four 512 by 512 polar stereographic fields. The first field gives the snow depth and sea-ice analysis, the second the snow age, the third the monthly snow/ice climatology and the fourth the manual bogus flags. Only the first field was analysed. The data consists of 2 byte integers and gives the snow depth in tenths of inches over land and is either 0 (water) or 4090 (sea-ice) over water. Also available on the ftp server is a USAF land mask file. The values are 1-sea, 2-land, 4-coast and 9-Southern Hemisphere. On reading in the USAF data, S.H. is converted to -9, sea is converted to -3, coast to -2, sea ice to -1 and the snow depth is converted to kg/m^2 . The conversion to kg/m^2 is empirical. $1/10\text{inch}$ of snow = 2.54 mm of snow and assuming that 1 mm water = x mm snow then the conversion factor is $2.54/x$. For fresh snow, a typical value of x might be 10 but $x=3$ was found to be a better match, see figure 27. The low value of x will, at least in part, be due to the aging of the snow packs but may also indicate that the UM is overestimating the snow depth or the IMS is underestimating the snow depth.

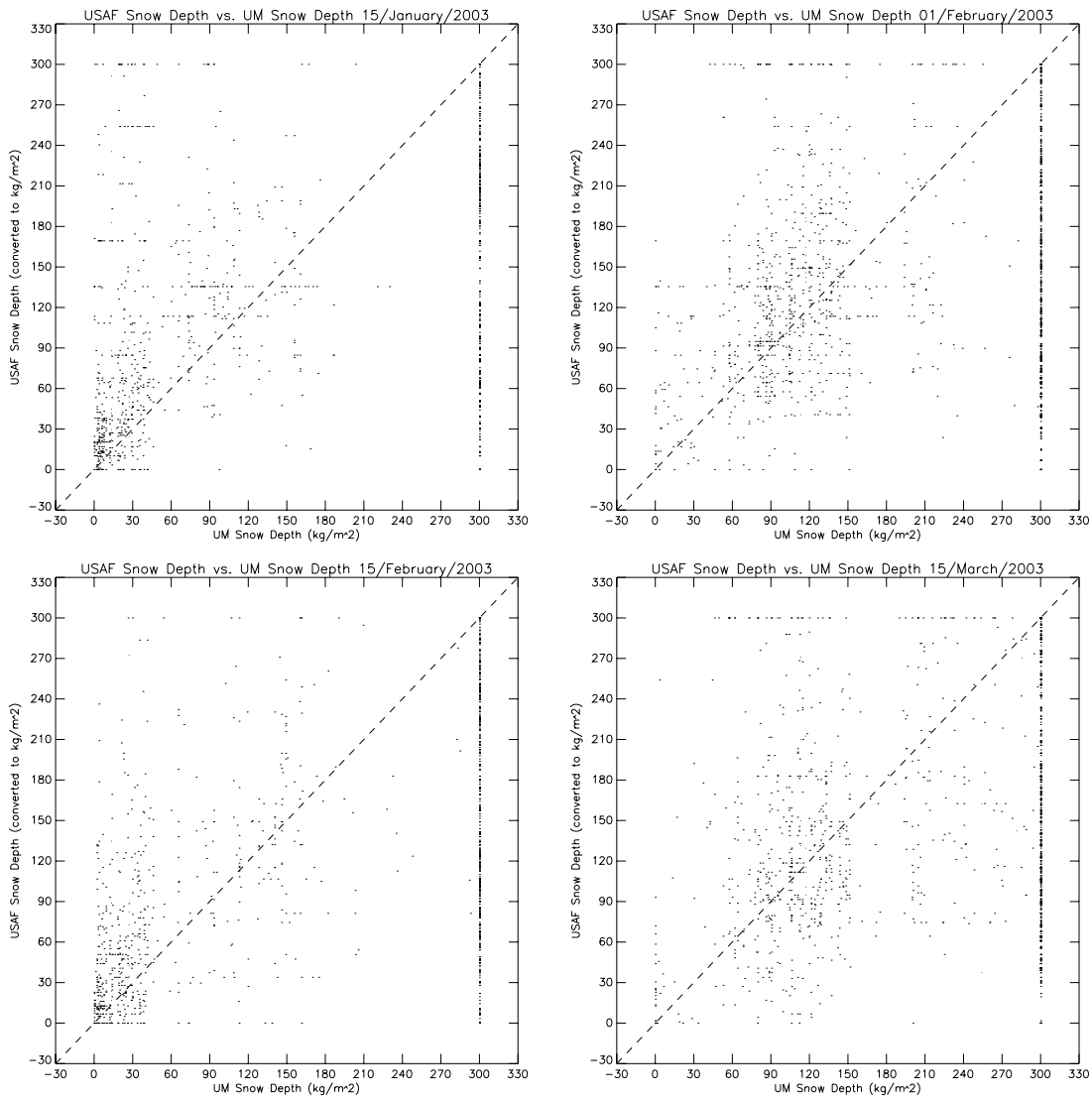


Figure 27: Comparison of the converted USAF snow amount with U.M. snow amount for 15th January, 1st February, 15th February and 15th March 2003.

The method for converting the data to latitude and longitude was the same as for IMS data. When reading the data in, the y-values had to be filled in reverse order to get a grid with the same orientation as the IMS data. The pole of the resulting grid was found to be $x=256$, $y=255$ (strangely, the pole is marked as coast in the land mask file). An exact separation between northern hemisphere and southern hemisphere was obtained with a radius of 249.63 but a value of 249.5 was used as it felt this was more likely (looking at a stripe through the pole in IMS data, there are 10 S.H. points on one side and 11 on the other, suggesting a radius of $(1024-21)/2=501.5$. With USAF data there are 6 S.H. points on one side and 7 on the other suggesting $(512-13)/2=249.5$).

4.2 Results

As was mentioned in section 3.1, the USAF analysis is one of the inputs to the IMS map. There is not, however, a complete match in the snow cover for these two data

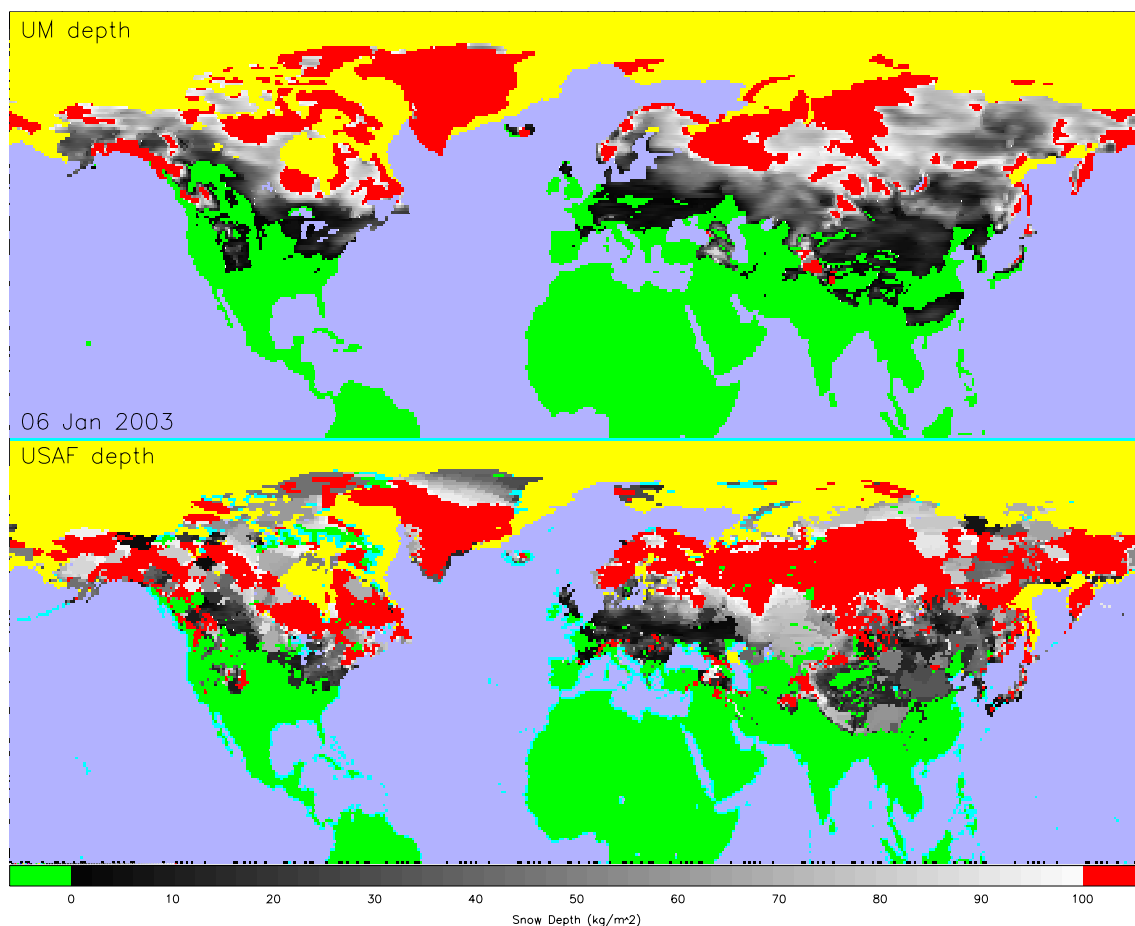


Figure 28: Comparison of UM and USAF snow depths for 6th January 2003.

sets. As the IMS snow cover is likely to be more reliable, the snow depth field was altered so that its depth was zero wherever there was no IMS snow cover and its depth was $1/10''$ wherever the IMS indicated snow cover but the USAF data had none. No time offset between the UM and USAF was assumed but the offset of 1 day between the UM and IMS was retained. Figure 28 compares the UM snow depth with the USAF snow depth (*not* adjusted to match the IMS snow cover) for 6th January 2003.

Figure 29 shows maps of the average snow depth difference between the UM and the IMS adjusted USAF for areas where they agree about snow cover, areas where there is IMS cover only and areas where there is UM cover only, calculated over the period 6th January 2003 to 31 March 2003. The UM reports deep snow depths over Greenland, northern Russia and northern Canada which tallies with figure 2. The rest of the plot looks very mottled and it is far from obvious what the regions of thick USAF/thin UM correspond to.

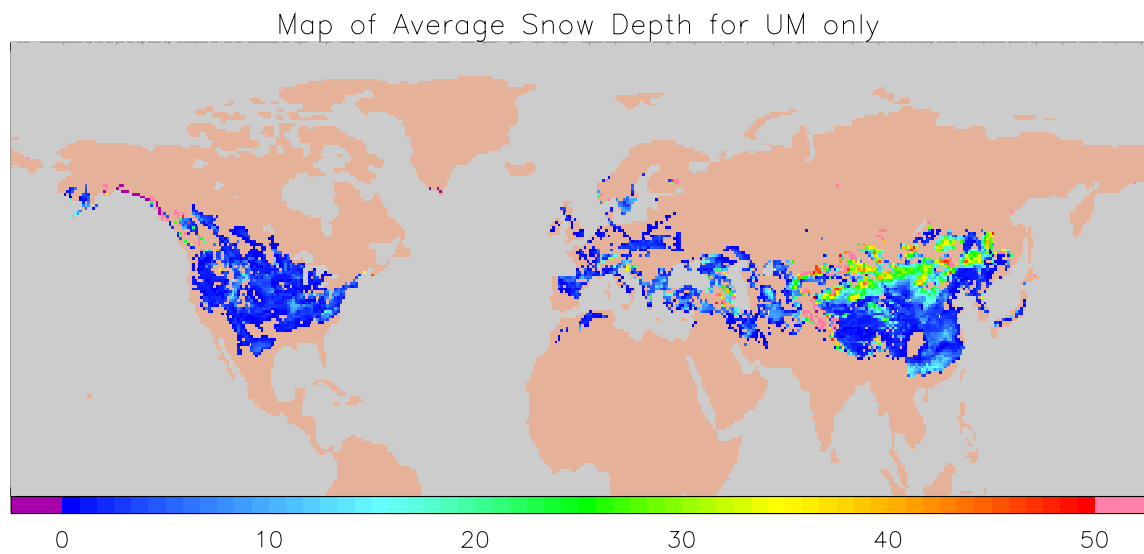
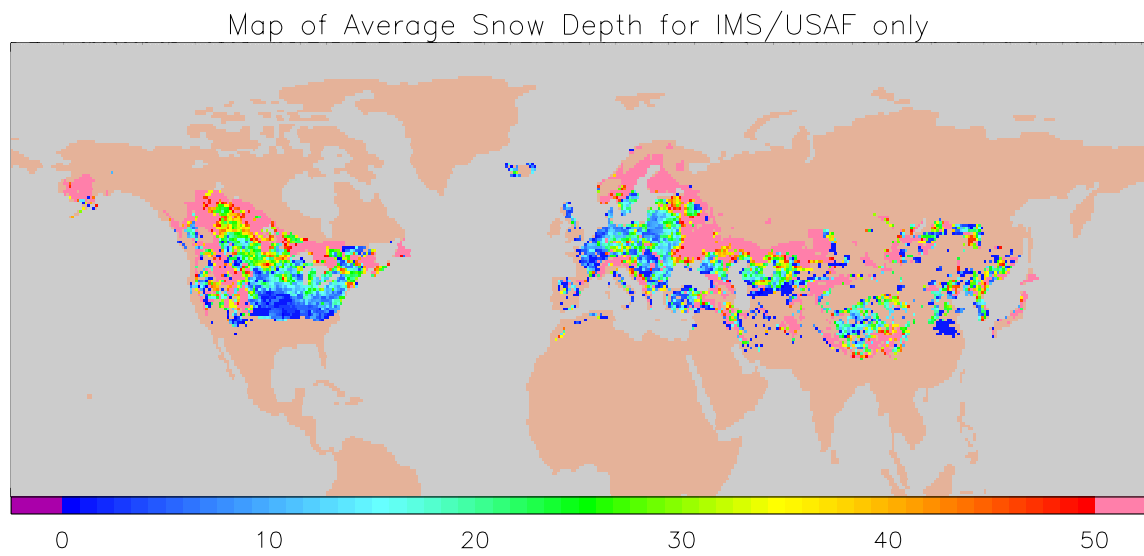
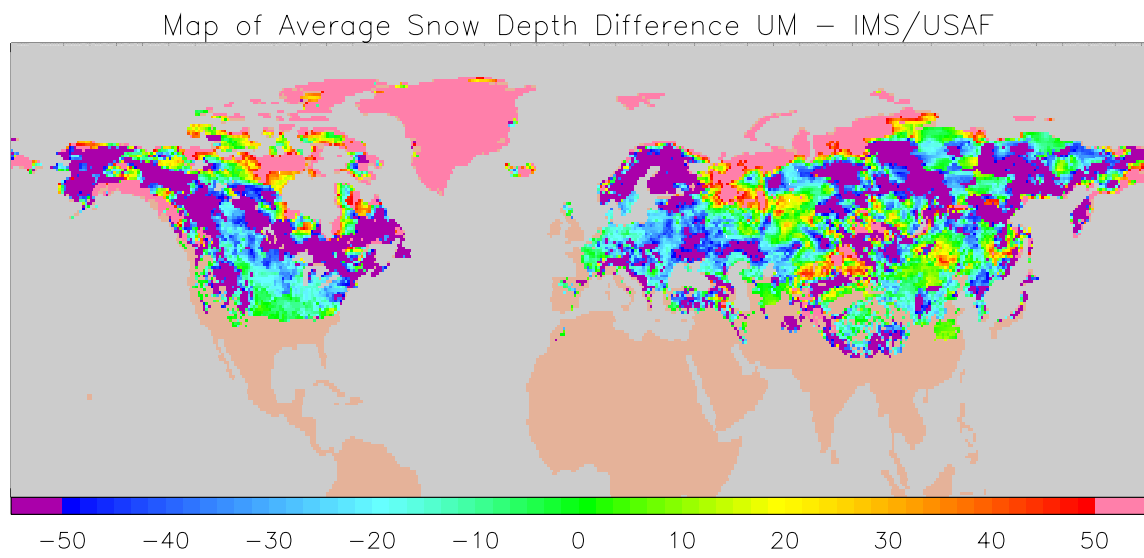


Figure 29: Average snow depth difference.

5 Summary

Unified Model (UM) snow and ice cover has been compared with the Interactive Multisensor (IMS) output for the 1st January 2002 to 1st August 2003. The following conclusions have been drawn:

- By the time the IMS output appears on the NCEP ftp server, the best correlation is with the UM field from 36 hours previously.
- The best correlation between the UM and IMS data is achieved if UM snow depths of 0.125 kg/m^2 (the smallest non-zero value) are treated as snow free.
- UM sea-ice cover is less extensive than the IMS and the cut-off at 0.5 sea-ice fraction should be reconsidered.
- Climatological sea-ice fields have occasionally appeared in the UM data. This problem has recently been fixed and should not be a problem in the future.
- Unphysical-looking holes can appear in the UM sea-ice field, especially around September when the Northern Hemisphere sea ice is at a minimum. It is tentatively suggested that missing satellite data could give this effect but this should be investigated.
- Snow cover seems to form fractionally too quickly in the UM at the start of winter and melts much too rapidly in the spring.
- The UM snow cover is more temporally variable than the IMS while the IMS seems to change more abruptly.
- The IMS tends to have more snow cover than the UM in the USA, Europe and north of the Caspian Sea.
- The UM has more snow cover than the IMS in parts of the Far East for the 2002/2003 winter.

A small set of USAF snow depth analyses has been collected. The method used to generate these analyses is interesting but the differences between these analyses and the UM are not easy to interpret. An internal Met. Office web page is available to view the UM/IMS and UM/USAF comparisons and provides a good way to get a subjective overview of the data. [7].

6 Future Work

The most striking difference between the UM and the IMS snow cover is that the UM snow cover melts far too rapidly in the spring. The reason for the rapid melt is not necessarily due to an inaccurate melting scheme but could be due to a multitude of other factors such as the UM diurnal cycle, cloud cover, water vapour, precipitation, etc. Assimilating the IMS, or other, snow product may not tackle the underlying problem.

Future work could include a comparison with ECMWF snow fields to help track down the most likely source of error, perhaps leading to a trial assimilation of the IMS data.

7 Acknowledgements

Roger Saunders and Jeff Ridley both provided much useful advice, guidance and feedback. Particular thanks goes to Vic Blackman for patiently explaining the wonders of COSMOS and finding several errors in my JCL job card (despite this assistance, COSMOS held on to some of its mystery and all of its contents).

Bruce Ramsay, Rob Fennimore and Susan Ladenheim (NOAA/NESIDS) were all very helpful in providing access to the Interactive Multisensor data, especially Rob Fennimore who ftp'd the complete IMS data set. Ying Lin (NOAA/NESDIS) kindly mailed me Kopp and Kiess paper when all that was requested was a reference.

A Other Snow and Ice Products

This appendix documents some other snow and ice products that came to light during this study.

The National Ice Center [11] offers a range of SSM/I near real-time products for sea-ice cover (85 GHz, Bristol, Bootstrap, CAL-VAL, NASA Team, NASA Team 2, NIC Hybrid [12]) with binary data files available for download. The web site has a brief description and reference for each method.

The National Snow and Ice Data Center [13] offers a very wide range of snow and ice products and data. Perhaps the most interesting is the 'Near Real-Time SSM/I EASE-Grid Daily Global Ice Concentration and Snow Extent' (NISE) [14]. The data is in Hierarchical Data Format - Earth Observing System (HDF-EOS) format and both hemispheres are covered. Importantly, the age of the observations seems to be recorded. If this product were to be used to adjust the model then we would prefer to assimilate only the up-to-date observations and leave the model to advance the rest of the snow field by itself. A known problem with SSM/I based snow products is that they can give inaccurate results for forests, wet snow and melting snow. Viewable .gif files are in the directory: `/data/nwp1/frbq/snow/nise/`. It might be interesting to verify this product against IMS data and the UM.

MODIS, the Moderate Resolution Imaging Spectroradiometer, has both snow cover and sea-ice cover products [15][16][17]. Unlike SSM/I, MODIS is an infrared instrument with 36 spectral bands between 0.4 and 14.4 μm . The MODIS product will presumably have different systematic biases compared with microwave data and might prove more reliable. Figure 30 shows MODIS data for 1st January 2003. MODIS will not be of use in persistently dark or cloudy areas.

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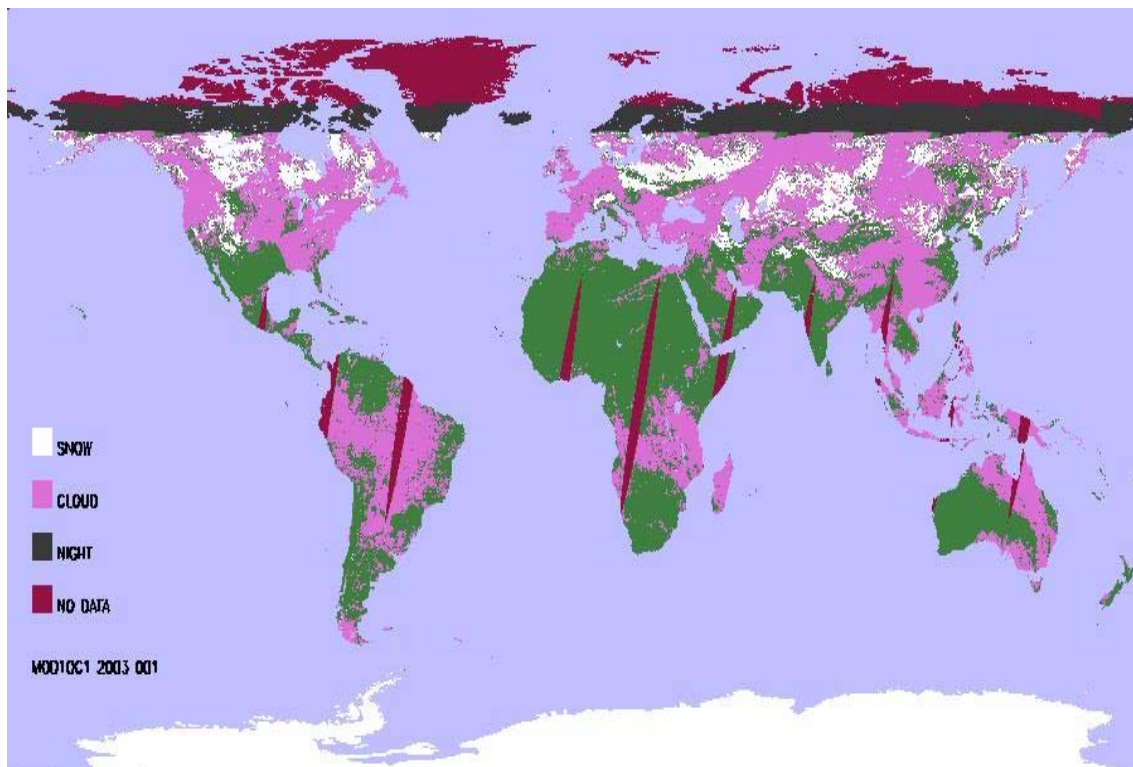


Figure 30: MODIS data for 1st January 2003.

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