The Centre for Australian Weather and Climate Research

A partnership between CSIRO and the Bureau of Meteorology

Testing and diagnosing the ability of the Bureau of Meteorology's Numerical Weather Prediction systems to support prediction of solar energy production

Paul A. Gregory, Lawrie Rikus and Jeffrey D. Kepert

CAWCR Technical Report No. 025

www.cawcr.gov.au

Testing and diagnosing the ability of the Bureau of Meteorology's Numerical Weather Prediction systems to support prediction of solar energy production

Paul A. Gregory[1], Lawrie Rikus[1] and Jeffrey D. Kepert[1]

[1]*The Centre for Australian Weather and Climate Research*
- a partnership between CSIRO and the Bureau of Meteorology

CAWCR Technical Report No. 025

July 2010

ISSN: 1835-9884

National Library of Australia Cataloguing-in-Publication entry

Title: Testing and diagnosing the ability of the Bureau of Meteorology's Numerical Weather Prediction systems to support prediction of solar energy production [electronic resource] / Paul A. Gregory, Lawrie Rikus and Jeffrey D. Kepert.

ISBN: 9781921605888 (pdf)

Series: CAWCR technical report; 25.

Notes: Included bibliography references and index.

Subjects: Australia. Bureau of Meteorology Research Centre. Numerical weather forecasting--Mathematical models. Weather forecasting--Australia-- mathematical models. Solar energy--Climatic factors--Australia. Solar radiation--Mathematical models.

Dewey Number: 551.52710994

Enquiries should be addressed to:

Dr Lawrie Rikus
ACCESS Model Evaluation Team.
Centre for Australian Weather & Climate Research
GPO Box 1289 Melbourne
Victoria 3001, Australia

l.rikus@bom.gov.au

Copyright and Disclaimer

CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

An assessment of the Bureau's ability to predict surface solar exposure using current Numerical Weather Prediction (NWP) models was conducted, with a view to assessing the Bureau's ability to support solar energy prediction.

Two current NWP models were examined for the 2008 Calendar year. Comparisons were made with estimates of surface radiation obtained from satellites for the whole Australian continent. Monthly averaged forecast solar exposure over Australia showed good agreement with satellite estimates, however the day-to-day exposure values showed some consistent errors. Errors in forecast exposure were usually attributed to incorrect computation of cloud properties in the tropics during summer, as well in south-eastern Australia and Tasmania. Detailed analysis within various latitude zones shows that computed monthly averaged exposure was continually over predicted in the tropics in the summer months, and continually over predicted for south-eastern Australia for the whole year. Spatial analysis showed that the NWP models could give good predictions of surface solar radiation at the middle latitudes.

Clouds in the summer tropics are often dominated by local convective clouds that are created during the day. These are at spatial scales not explicitly described by the models and it is known that the current NWP models use a very simple scheme to predict their presence as well as the radiation transmission through them.

Clouds over south-east Australia are often created due to orographic lifting around the Great Dividing Range, and indeed many of the errors in the minimum value of the exposure are seen in the vicinity of these ranges. It is possible that the satellite algorithm may be incorrect over high topography due to the presence of snow etc. Note also that the satellite processing does not account for the variation of Rayleigh scattering with altitude, or effects due to topography such as incidence angle, shadowing, etc.

Comparison with site-based exposure observations was conducted at eight locations across Australia. This analysis was conducted on a daily and hourly basis. The site-based exposure measurements echoed the findings from the spatial analysis against satellite data, i.e. the NWP values for exposure were often greater than the site values, especially in the tropics during summer. The daily analysis at lower latitudes showed that the NWP forecast could track the qualitative behaviour of the site-based observations, but it would often over predict the exposure value for days of heavy cloud cover, particularly for high level cloud. During winter, the NWP often showed better estimates of exposure than the satellite data.

Hourly analysis at selected sites confirmed that NWP were able to predict the solar exposure accurately through low-level clouds (e.g. Cumulus), provided that the forecast cloud coverage was accurate. The NWP struggles to predict solar exposure through high clouds (e.g. Altocumulus). Sites located at the middle latitudes showed that the NWP could provide forecasts of solar exposure to within 5-10% up to two days in advance.

Although the current NWP models struggle in some areas of the Australian continent (due to particular cloud types created in these regions) the analysis shows that the NWP models can forecast solar exposure at likely solar power plant locations. Preliminary analysis of the ACCESS model showed it gave significant improvements in the computation of solar irradiance

through high clouds relative to the previous models. It is recommended that the preliminary analysis presented for the ACCESS model be extended when it becomes operational in order to test the future capability of the Bureau to support solar energy prediction.

1 INTRODUCTION

This section of the report gives a brief background of the physics and terminology used to describe solar radiation. The measurement techniques (both ground-based and satellite) are discussed, as well as a brief outline of the algorithms used in the NWP models.

1.1 Solar radiation

The sun is essentially a large thermonuclear reactor that is the original source of all energy in the atmosphere. The external surface of the sun can be treated as a blackbody radiating at a temperature of 5800K.

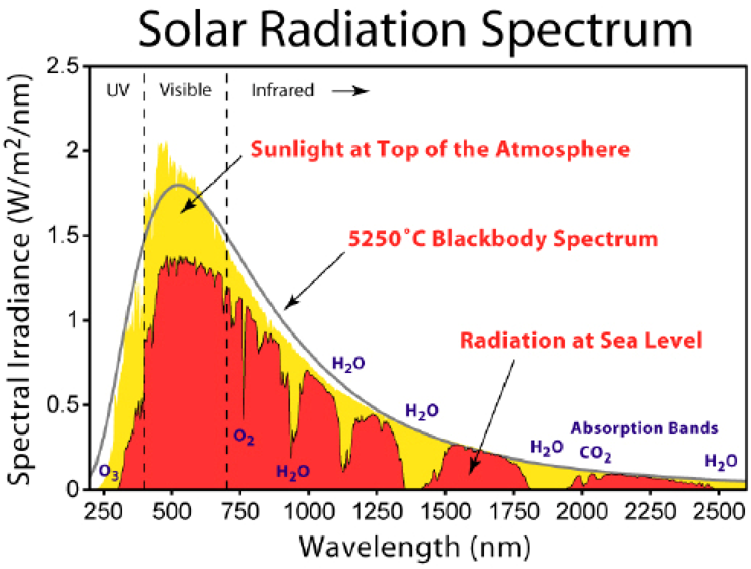

Fig. 1 The Solar Radiation Spectrum (from Wikipedia.com)

Figure 1 shows the solar radiation spectrum. The sun emits radiation across a wide range of wavelengths. A large component of the sun's energy is absorbed by various gases (e.g. Ozone, Water Vapour, Carbon Dioxide) or scattered by gaseous molecules, airborne particles and cloud within the atmosphere before it reaches the earth's surface. The units for spectral irradiance in fig. 1 are W/m2 nm, which implies that the computed radiation is dependent on the limits of the integration performed in wavelength space.

The amount of solar radiation reaching a point on the earth is dependent upon the time of the year, as well as the latitude of the particular point. As we know, it takes 365 days for the earth to complete one orbit of the sun, where each day is 24 hours long. The day is defined as the time taken to make one rotation about its axis.[1]

[1]The exact length of one rotation, or one sidereal day is 23 hrs, 56 minutes, 4.09 seconds, and the exact year is 365.242 mean solar days. The mean solar day is referenced to the direction of the sun and is exactly 24 hours.

Since the plane of the equator is inclined at 23.5 degrees from the plane of earth's orbit, the maximum angle of the sun above the horizon (azimuth angle) varies during the course of the year. At December 22^{nd}[2] (the summer solstice) the sun is directly overhead at noon at latitude 23.5◦S (the Tropic of Capricorn). Likewise, at June 22nd (the Winter solstice) the sun is directly overhead at noon at 23.5◦S (Tropic of Cancer).

The lengthening or shortening of the period of daylight at a given latitude follows the variation of the maximum azimuth angle which varies over the course of the year as the earth orbits the sun. The actual angle of the sun from the zenith (i.e. directly above the observer) depends on the local value of latitude where the observation is taking place, the time of day and the day of the year. This angle is defined as the solar zenith angle ζ.

At times of the year when the maximum daily ζ is small (i.e. summer) the amount of radiation reaching the observer is large due to the sun shining more directly (and therefore with more intensity) on the surface of the earth. Associated with the seasonal variation in maximum azimuth angle there is a variation in the length of the day. This naturally affects the amount of radiation accumulated during the day.

1.2 Measuring solar radiation

Solar irradiance is usually measured as a flux of energy per area with units of watts per square metre. This is known as the irradiance, and is a measure of the rate of energy received per unit area. Radiant exposure is a time integral (or sum) of irradiance, and has units of joules per square metre.

Solar radiation can be decomposed into two components; direct and diffuse. Direct solar exposure is the rate of solar energy arriving at the Earth's surface from the direction of the Sun onto a plane perpendicular to the beam. This is usually denoted as direct normal exposure, or direct solar exposure on a horizontal plane is also sometimes used. It is usually measured by the temperature change on an absorbing element with a known temperature response function (e.g. a blackened silver disk). This element is known as a pyrheliometer and it has a restricted field of view of the order of five degrees.

Diffuse solar irradiance is a measure of the rate of solar energy arriving at the Earth's surface which has been scattered by the atmosphere (i.e. from directions away from the direct path to the sun). This scattering is created by interactions with gaseous molecules (e.g. N2, O2,H2O), atmospheric aerosols, ice and water droplets etc.

Diffuse irradiance is measured using a pyranometer shielded from the sun. The diffuse and direct exposures are measures of accumulated energy and are defined by time integrals of the relevant irradiances. Diffuse solar exposure will always be less than or equal to the global solar exposure. All Bureau of Meteorology radiation observation stations record separate measurements of global, direct and diffuse radiation. These three quantities are linked according to the formula

$$E_g = E_d + E_b \cos \zeta, \tag{1.1}$$

[2] The exact day may vary on account of leap years

where E_g is global exposure, E_d is diffuse exposure, E_b is the direct exposure due to the sun's beam and ζ is the zenith angle.

On a clear-sky day, almost all of the measured irradiance will be direct. A small amount of diffuse irradiance is always present, as this is created from the radiation scattered throughout the atmosphere due to Rayleigh scattering. During an overcast day, clouds will both reflect and absorb incoming shortwave irradiance. The shortwave irradiance that is transmitted through the cloud and reaches the earth will be entirely diffuse. The amount of irradiance that is transmitted through a cloud is related to its optical depth, or optical thickness. Optical depth is a measure of how transparent a cloud is to incoming solar irradiance. A light, high cloud such as cirrus transmits a large amount of shortwave irradiance; hence it has small values of optical thickness. A heavy, low cloud such as cumulus will transmit less shortwave irradiance; hence it will have a greater value of optical thickness.

1.3 Satellite estimates of solar radiation

The satellite does not directly measure exposure at the surface. However, the surface exposure can be inferred from the outgoing radiation at the top of the atmosphere for a spectral band in the visible part of the solar spectrum, using a set of algorithms to derive the effects of cloud etc. The algorithms can be bias corrected by comparing with the surface site based data which are unfortunately limited in both number and distribution over the Australian continent. The benefit of the satellite derived data is that it is produced over the entire continent and is the only estimate available for most regions. However it should not be regarded as the 'exact' answer; satellite derived surface irradiance still depends on a model for cloud effects for example.

1.4 Numerical computation of solar radiation

Calculations of radiation in the atmosphere are made by discretising the atmosphere into various vertical layers. Each layer contains quantities for water vapour, aerosols, cloud properties as well as atmospheric concentration of gases. The radiation fluxes are computed through each layer for each spectral band. The radiation flux calculations depend on transmission and reflection coefficients for both direct and diffuse radiation. These coefficients are in turn related to the layer's optical properties.

1.5 Section summary

Solar radiation measured by an observer at the surface of the earth is denoted as solar irradiance. Accumulating solar irradiance over a certain time period (such as an hour or a day) gives the solar exposure per hour or day. The amount of solar exposure reaching the earth is primarily dictated by the solar zenith angle, which is the angle of the sun above the horizon. This is determined by the latitude of the observer, the time of the day, and the day of the year.

The amount of cloud in the sky is also a significant factor in determining the amount of exposure that reaches the observer. Additionally, cloud coverage affects the amount of diffuse and direct exposure that is measured at the surface. Satellites make estimates of surface exposure based upon radiance measurements of the top of the atmosphere; however these are not exact measurements and must always be checked against ground-based data.

2 METHODOLOGY

The aim of the project is to assess the performance of Bureau NWP systems in the prediction of surface solar exposure. This assessment was predominantly based on satellite data obtained for the whole Australian continent. Ground-based measurements obtained at several sites within Australia provide an independent method to check the accuracy of both the NWP and satellite results. Further details of the NWP systems, satellite measurements and the ground-based measurements are given in this section.

2.1 Forecast data

The total surface solar irradiance from the current operational regional model (LAPS) and the mesoscale assimilation model (MALAPS) have been archived as part of the operational forecast suite for each hour of the forecasts made twice daily. The LAPS model has a resolution of 0.375◦ (37.5 km) and provides 72 hour forecasts, while the MALAPS model has a resolution of 0.1◦ (10.0 km) and provides 48 hour forecasts data. Results for both models have been processed for the entire 2008 Calendar year.

The surface solar exposure for these models has been calculated for direct comparison with a product derived from satellite data. Daily exposure is computed by summing the hourly surface irradiance over daylight hours and converting it to solar exposure by assuming it to be constant over each hourly timestep. The operational forecast starting at 12UTC encompasses two complete solar days (~ 18UTC to ~ 12UTC) and these have been evaluated separately as the 1st and 2nd day forecasts for solar exposure. The LAPS model allows the computation of an additional 3rd day solar forecast. The 00UTC forecasts were ignored as they only encompassed one complete solar day for the 48 hour forecast (MALAPS), or two solar days for the 72 hour forecast (LAPS).

The radiative transfer parameterization in the current operational NWP models has a number of simplifications which have ramifications for the present study. The most important of these is the assumption that all incoming radiation becomes diffuse at the top-most level of cloud, regardless of the magnitude of the cloud fraction. This probably introduces biases on days with thin high cloud cover. The next generation of NWP models based on the ACCESS system have a radiative transfer scheme which maintains the distinction between the direct and diffuse components without this limitation and should, therefore, give better results in thin cloud conditions.

2.2 Satellite data

The validation data is sourced from an updated version of the Bureau's surface solar exposure product. This is derived using hourly geostationary satellite data (see Grant and Muirhead 2009) and validated against data from a small number of surface radiation sites. The hourly irradiances are integrated to daily exposure by linear interpolation between hours. It has a nominal horizontal resolution of 0.05◦ (5km), which necessitates the regridding of the satellite data to the model grid for direct comparison. The background to the satellite data processing is covered in Weymouth and Le Marshall 2001, Grant et al. 2008.

Table 1 Location of sites which record ground-based exposure measurements.

Description	Latitude	Longitude
Melbourne Airport	-37◦ 40' 30.00"	144◦ 50' 31.80"
Wagga Wagga	-35◦ 9' 35.40"	147◦ 27' 22.20"
Rockhampton	-23◦ 22' 37.20"	150◦ 28' 35.40"
Alice Springs	-23◦ 47' 41.99"	133◦ 53' 20.56"
Darwin	-12◦ 25' 27.00"	130◦ 53' 33.00"
Broome	-17◦ 56' 55.80"	122◦ 14' 2.40"
Adelaide	-34◦ 57' 6.00"	138◦ 31' 16.80"
Cape Grim	-40◦ 40' 54.00"	144◦ 41' 21.00"

2.3 Site data

The Bureau maintains a country-wide radiation network which records direct, diffuse and global downwards short-wave solar exposure and is available as half-hourly averages. Each site is close to a Bureau observation site with observed cloud data which enables further assessment of the NWP systems to predict exposure through various cloud types. The list of the radiation sites used in this report is given in table 1. The locations of these sites are shown in fig. 2.

The half-hourly measurements recorded at each site were converted to hourly accumulations to enable comparisons to the NWP systems and satellite observations.

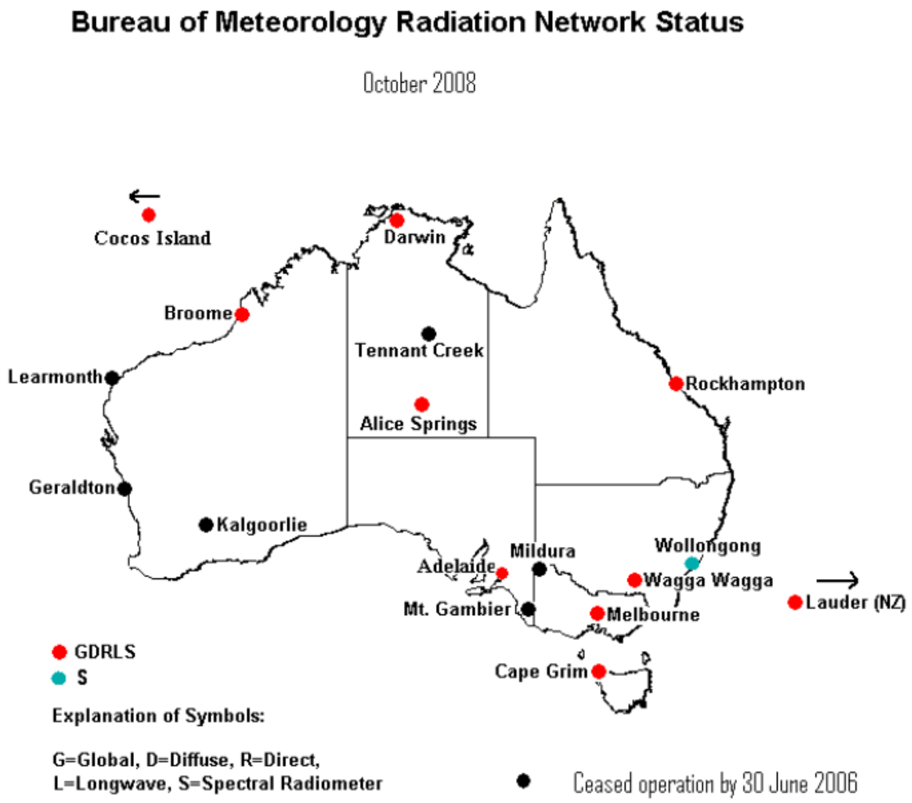

Fig. 2 Location of exposure observation sites given in table 1

2.4 Section summary

This section gave further details of the NWP models used to assess the performance of Bureau NWP systems in the prediction of surface solar exposure. Additional details of the satellite measurement resolution and the ground-based measurement locations were also provided.

3 RESULTS – AUSTRALIA WIDE

Results for NWP forecasts are presented in this section and are compared to the equivalent satellite results. These results are for solar exposure across the whole of Australia.

3.1 Yearly results

Results for the monthly-averaged solar exposure from the forecast models for the 2008 calendar year are presented in fig. 3 and fig. 4, along with the differences from the computed satellite values averaged over the Australian continent. In these plots, the accumulated solar exposure averaged over each month for the LAPS and MALAPS models is plotted against the equivalent satellite derived data and the differences are normalized at each point by the average spatial deviation for that month.

Results for the MALAPS model in fig. 3 show that the forecasts tend to overestimate solar exposure levels during the warmer months, but achieves better agreement with the satellite data during the winter. The model tends to underestimate levels of solar exposure relative to the satellite during the autumnal months. There are noticeable differences between the 1st and 2nd day solar forecasts from October through to December, but for the majority of the year there is little to choose between them. The closer agreement over the winter months is also a consequence of the lower values in average exposure received during this period.

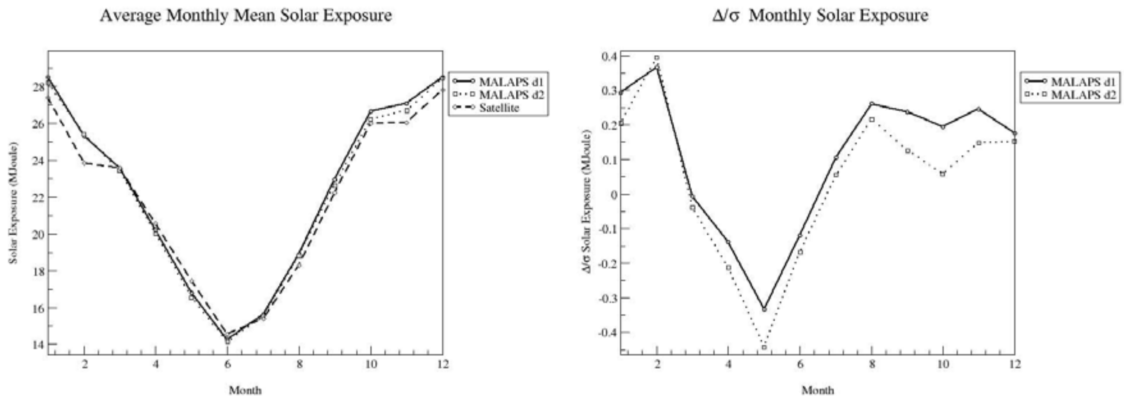

Fig. 3 Averaged monthly mean daily solar exposure over continental Australia for the MALAPS model (left) with differences between the MALAPS and satellite data (right). The suffixes 'd1' and 'd2' refer to 1st and 2nd day forecasts respectively.

These trends are repeated for the LAPS model shown in fig. 4. However, the LAPS model shows better agreement in the summer months, with worsening agreement over the autumn.

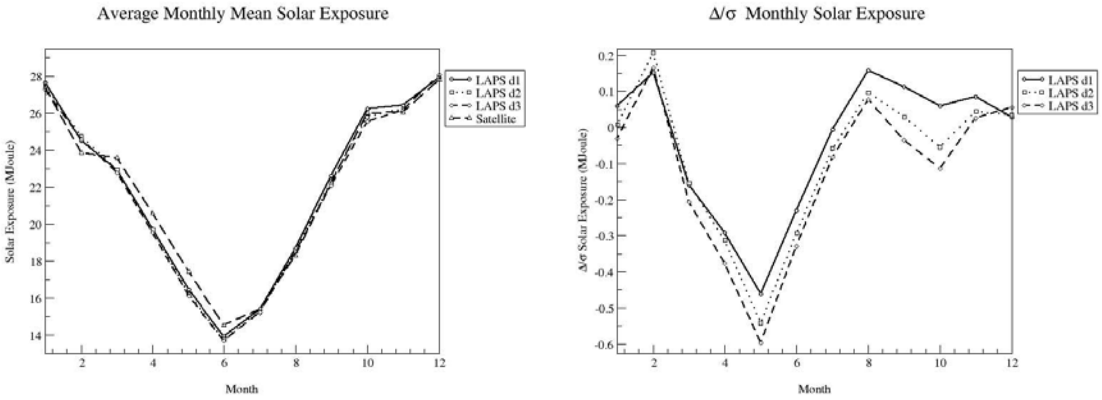

Fig. 4 Averaged monthly mean daily solar exposure over continental Australia for the LAPS model (left) with differences between the LAPS and satellite data (right). The suffixes 'd1', 'd2' and 'd3' refer to 1st, 2nd and 3rd day forecasts respectively.

3.2 Monthly results

Average RMS errors for each month of MALAPS forecasts are shown in table 2. The average RMS error was calculated by computing the RMS error between the MALAPS data and satellite data for each day during a given month, and then averaging this value. Finally, the value is normalized by the mean exposure for that month, to ensure that error is comparable across summer to winter. The corresponding data for the LAPS forecasts is shown in table 3.

The results in tables 2 and 3 show that the extended forecasts for each model produce similar accuracy for the daily solar forecast when averaged over the whole of Australia. The results also highlight the trends observed earlier, namely that the MALAPS forecasts do better in the winter months versus the summer months, whereas errors in the LAPS models are distributed more evenly throughout the year.

The results also highlight the increased variability of solar exposure observed during the summer months. This is mainly a consequence of the larger exposure values during these months although seasonal variation in cloud type and thickness also play a role. Any obscuration of the sun's direct beams by cloud cover causes a larger relative drop in exposure, when compared to a similar event occurring in winter.

Plots of daily exposure for selected months are shown in fig. 5 and fig. 6 for each NWP system. The months selected for detailed analysis are January, May, July and November, which are representative of summer, autumn, winter and spring conditions respectively.

For the MALAPS results, the January results show the NWP data consistently overestimates the magnitude of the average solar exposure derived from satellite data, although it is able to follow the trend of the data during the month very well. The offset between the NWP and satellite data is of the order 5-10%. During May, this trend has reversed, and the magnitude of the NWP data is less than the corresponding satellite data. Once again, the difference is of the order 5-10%, although towards the end of this month, the agreement is quite good. During July, the trend for the NWP to overestimate exposure has returned, however it is not as consistent as that observed during January.

Table 2 *Average RMS errors and standard deviation for each month using the MALAPS model.*

	MALAPS 1stday			MALAPS 2ndday		
Month	RMS error	μ	σ	RMS error	μ	σ
January	0.042670	28.51	1.0763	0.03741	28.35	1.1362
February	0.05437	25.23	1.0254	0.05649	25.29	0.8894
March	0.02137	23.62	2.2890	0.02324	23.60	2.2322
April	0.021130	20.29	1.2077	0.02404	20.17	1.1993
May	0.03429	16.86	1.0207	0.04639	16.66	0.9751
June	0.03085	14.23	0.9409	0.03488	14.10	0.9183
July	0.02725	15.57	0.5934	0.02920	15.43	0.5879
August	0.03072	18.88	0.8065	0.02946	18.74	0.9422
September	0.02981	22.90	1.8841	0.01929	22.51	1.8617
October	0.02638	26.68	1.4172	0.01907	26.26	1.5466
November	0.04277	26.99	1.4384	0.03648	26.51	1.5749
December	0.04179	28.52	1.3376	0.03130	28.38	1.3713

Table 3 *Average RMS errors and standard deviation for each month using the LAPS model.*

	LAPS 1stday			LAPS 2ndday			LAPS 3rdday		
Month	RMS error	μ	σ	RMS error	μ	σ	RMS error	μ	σ
January	0.03302	27.76	1.3265	0.03058	27.63	1.3345	0.03343	27.58	1.2318
February	0.03434	24.42	1.1070	0.03618	24.60	1.0219	0.03903	24.44	1.0559
March	0.03642	22.99	2.4855	0.03651	23.11	2.3555	0.04311	22.96	2.3024
April	0.03832	19.81	1.1818	0.03730	19.85	1.1845	0.04554	19.73	1.2336
May	0.05527	16.52	1.0663	0.06676	16.34	1.037	0.07216	16.26	0.9991
June	0.04764	13.91	1.0700	0.05842	13.73	1.076	0.06729	13.64	1.0547
July	0.03124	15.34	0.6422	0.03616	15.19	0.6138	0.03970	15.10	0.6411
August	0.02185	18.67	0.8174	0.02250	18.50	0.9744	0.02372	18.40	1.0116
September	0.02045	22.54	1.9121	0.01623	22.21	1.8762	0.02457	21.95	1.8630
October	0.01628	26.26	1.4884	0.02084	25.84	1.5994	0.02371	25.63	1.5514
November	0.04066	26.31	1.5087	0.04106	26.06	1.5822	0.04722	25.86	1.5163
December	0.02555	27.94	1.4619	0.02605	27.91	1.4984	0.02851	27.93	1.6930

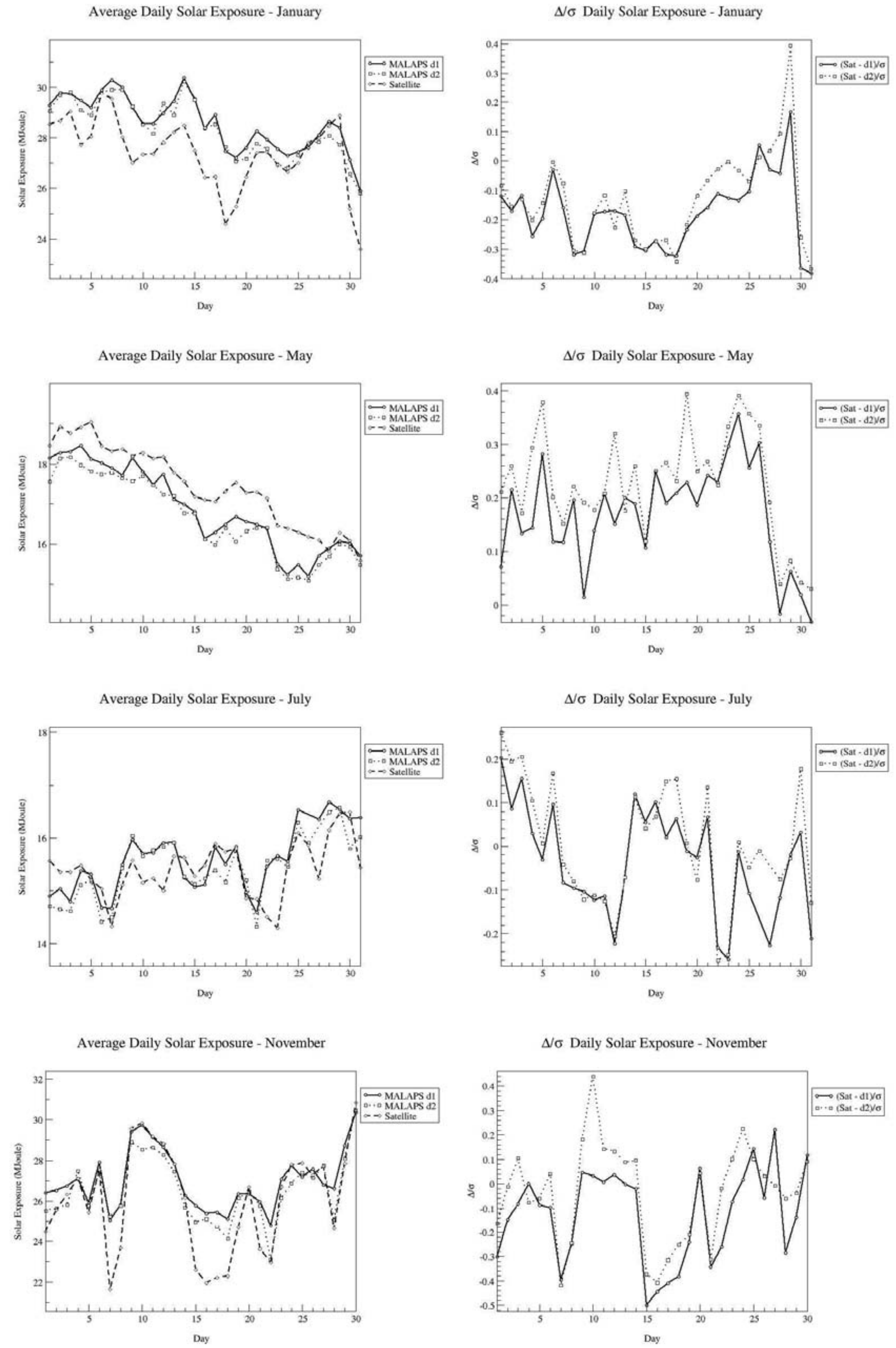

Fig. 5 Plots of daily solar exposure averaged over continental Australia for both MALAPS forecasts (left). The difference between the satellite data and NWP data (right) is normalized by the satellite spatial standard deviation for the corresponding day. The suffixes ‘d1’ and ‘d2’ refer to 1st and 2nd day forecasts respectively.

Fig. 6 Plots of daily solar exposure averaged over continental Australia for both LAPS forecasts (left). The difference between the satellite data and NWP data (right) is normalized by the satellite spatial standard deviation for the corresponding day. The suffixes 'd1', 'd2' and 'd3' refer to 1st, 2nd and 3rd day forecasts respectively.

The trend for November is similar to January; although there is very good agreement for some days (particularly November 9th, 14th and 23rd -27th), there are also some days where the NWP overestimates the satellite data by 10-20%. Over these four particular months, the behaviour of the 1st and 2nd-day forecasts are very similar.

The LAPS results for January are quite different to the MALAPS results. There is no constant trend, with the NWP average exposure greater than the satellite data for the beginning of the month, and less than the satellite data between January 21st-30th. The LAPS results for the following months are very similar to the corresponding MALAPS results. The plots of Δ/σ show that the error does increase for the 3rd forecast day.

The analysis for each month shows little difference between the two NWP systems, despite the large differences in resolution. Additionally, the NWP results show little variation with each additional forecast day.

The results show that the existing NWP systems can provide accurate qualitative predictions of daily mean solar radiation, up to three days in advance. The movement of major cloud bands (which is responsible for day-to-day irradiance attenuation) is shown to be accurately predicted. However, the degree of attenuation caused by the cloud bands is still subject to some variation relative to the satellite derived data. The question of whether the model or the satellite algorithm for cloud effects is closest to reality will be considered further in § 5 which compares both methods with surface site measurement data.

3.3 Monthly results - spatial analysis

The analysis presented previously in fig. 5 and fig. 6 concentrated on the average value of daily accumulated solar exposure calculated across Australia for each day. However, this doesn't take into account the spatial variation in solar exposure for each day. Solar irradiance varies with latitude and is also dependent on local cloud cover. Additional information is required to determine the source of errors for averaged solar exposure.

Further analysis of the monthly results can be achieved by calculating the Probability Density Function (PDF) for the monthly mean daily accumulated solar exposure over the continental grid points for each month. In conjunction with a standard colour plot, the PDF enables the spatial distribution of the NWP results to be compared against the satellite data by showing the relative amount of each average exposure value present for a given month. Examining the 'tails' of the PDF, as well as the location of the 'peak' can reveal more details of the types of conditions which can lead to the differences between the spatially-averaged monthly NWP forecast and the satellite data. Clear-sky conditions will produce a PDF with higher exposure values (i.e. shifted to the right), whereas more frequent cloud cover will produce lower exposure values which will tend to shift the PDF to the left (see fig. 7).

Figure 8 shows computed PDFs and colour plots of averaged solar exposure for the MALAPS forecasts and satellite data. For January, the colour plots for the model show a consistent spatial pattern across both forecast days with slightly more spread of attenuated values for the second day. The corresponding PDFs show a small shift in the peak towards cloudier conditions with increasing forecast day. The PDF for the satellite data agrees well with the model peaks but the tails of the PDFs for low exposure values are very different. The satellite PDF has more data points with exposure values less than 25 MJ/m2 .

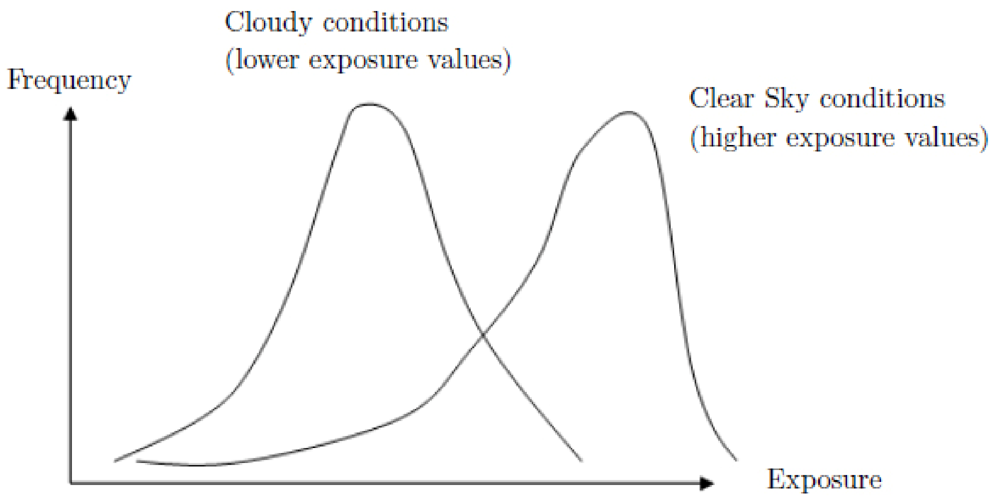

Fig. 7 Example of PDFs for a clear and cloudy sky conditions.

The colour plots shows that these regions of lower exposure are concentrated in the tropics (particularly near Cape York), and extending south along the eastern coast. The trend extends along the Great Dividing Range.

The results for May are significantly different. The PDF shapes are much rounder and broader, which is partly due to more cloud attenuation of exposure values over the month; the changing of the solar zenith angle with season also contributes to a broader PDF for clear skies. The NWP and satellite PDFs show only slight differences. The colour plots confirm this, as the spatial signatures across all of Australia are very similar.

Figure 9 shows the same results for the months of July and November. The July results are essentially the same as May. Both the NWP and satellite PDFs are relatively rounded and 'squat' in shape, with only small differences between them. The colour plots show a very similar spatial signature across Australia. The similarity of the satellite and model derived results for May and July and the shapes of the insolation patterns and PDFs are a strong indication that the model is able to capture the cloud associated with the predominately frontal events which dominate the weather in the south of the continent during those months.

However, for November, large differences are again observed. The peak of the satellite PDF has a very different shape, as does the tail for values < 22 MJ/m2. The colour plots show similar patterns to those observed in January except that the PDF peak is shifted towards lower insolation values indicative of a systematic cloud regime during the month. In particular the satellite data shows much lower exposure values along the eastern seaboard, in particular east of the Great Dividing Range, and in Tasmania. The main differences are due to the fact that the satellite data shows evidence of large cloud features over central and south-eastern Australia which the NWP models have not predicted. However, there is still reasonable agreement in the tropics.

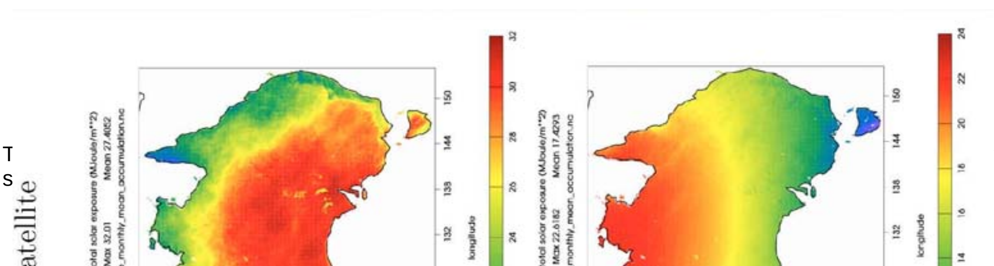

Fig. 8 Spatial analysis of monthly averaged solar exposure for January and May. From L to R: PDF distributions for MALAPS and satellite data, colour plots for MALAPS 1st day forecast, MALAPS 2nd day forecast and satellite data

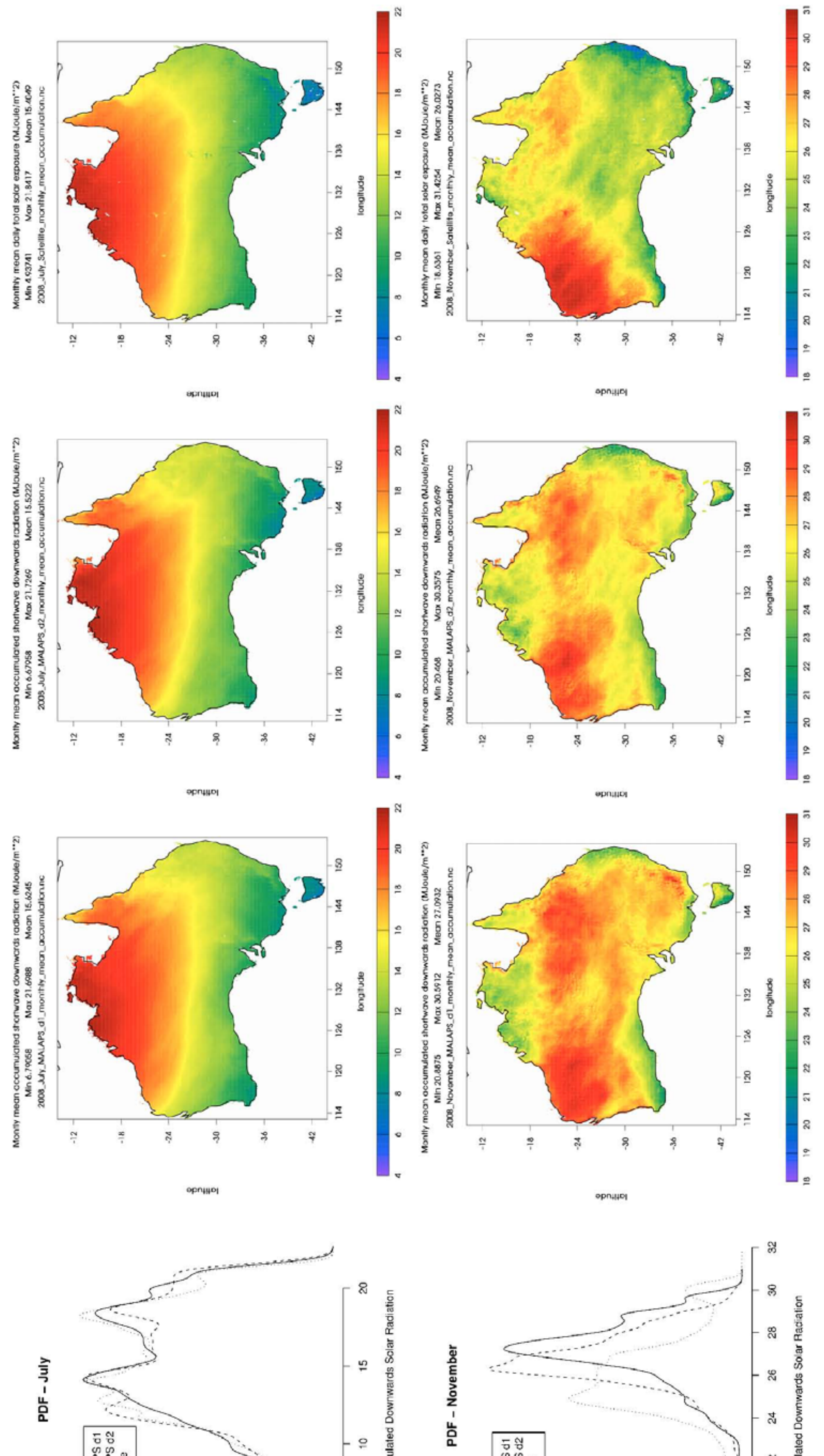

Fig. 9 Spatial analysis of monthly averaged solar exposure for July and November. From L to R: PDF distributions for MALAPS and satellite data, colour plots for MALAPS 1st day forecast, MALAPS 2nd day forecast and satellite data

3.4 Monthly results - zonal spacial analysis

Further analysis of the spatial distribution of the monthly averaged solar exposure can be achieved by breaking the analysis into different latitude zones for the tropics, as well as central and south eastern Australia, as defined in table 4 below.

Table 4 *Description of three spatial zones.*

Zone	Description	Latitude Range (min-max)
1	Tropics	−24.0◦ to −10.0◦
2	Central Australia	−36.0◦ to −24.0◦
3	Victoria and Tasmania	−48.0◦ to −36.0◦

The zonal analysis of monthly averaged solar radiation is shown in figures 10 to 12. For brevity's sake, only results from January, May and November are shown in these figures.

The zonal results for January highlight the difficulty the NWP systems have in predicting solar exposure in the tropics during the summer with its associated convective activity around the coast. The PDFs and colour plots for this region highlight the increased solar attenuation over the tropics and Cape York due to increased cloud cover. The results at the middle latitudes (zone 2) show much better agreement, with the region to the east of the Great Dividing Range only showing a small error. Finally, the results for lower latitudes (zone 3) again show some discrepancies in attenuation near the Alps and Tasmania.

Repeating the zonal analysis for May shows that the NWP results have much better spatial agreement with the satellite data as expected from the continental analysis in the previous section. For all zones, the model PDFs show much better agreement with the overall satellite distribution, although the NWP results show more solar attenuation than the satellite data for middle and high latitudes, implying that the model's cloud is either too frequent or too optically thick relative to that derived by the satellite algorithms.

Examining the zonal results for November highlights again the discrepancies in the tropics during the warmer months. Although the attenuation levels (i.e. minimum values of solar exposure) are quite close for both the NWP and satellite results, the NWP predictions show less cloud forming (on average) during the month, with larger regions of clearer skies, particularly over central Queensland. This is apparent in the shapes of the PDFs; the NWP and satellite results. The majority of the satellite exposure values fall in the band between 25-28 MJ/m2, where the NWP results produce the majority of exposure between 26-29 MJ/m2 . This discrepancy is also evident at middle and higher latitudes and the PDFs clearly show the satellite peak shifted to the left relative to the NWP curves.

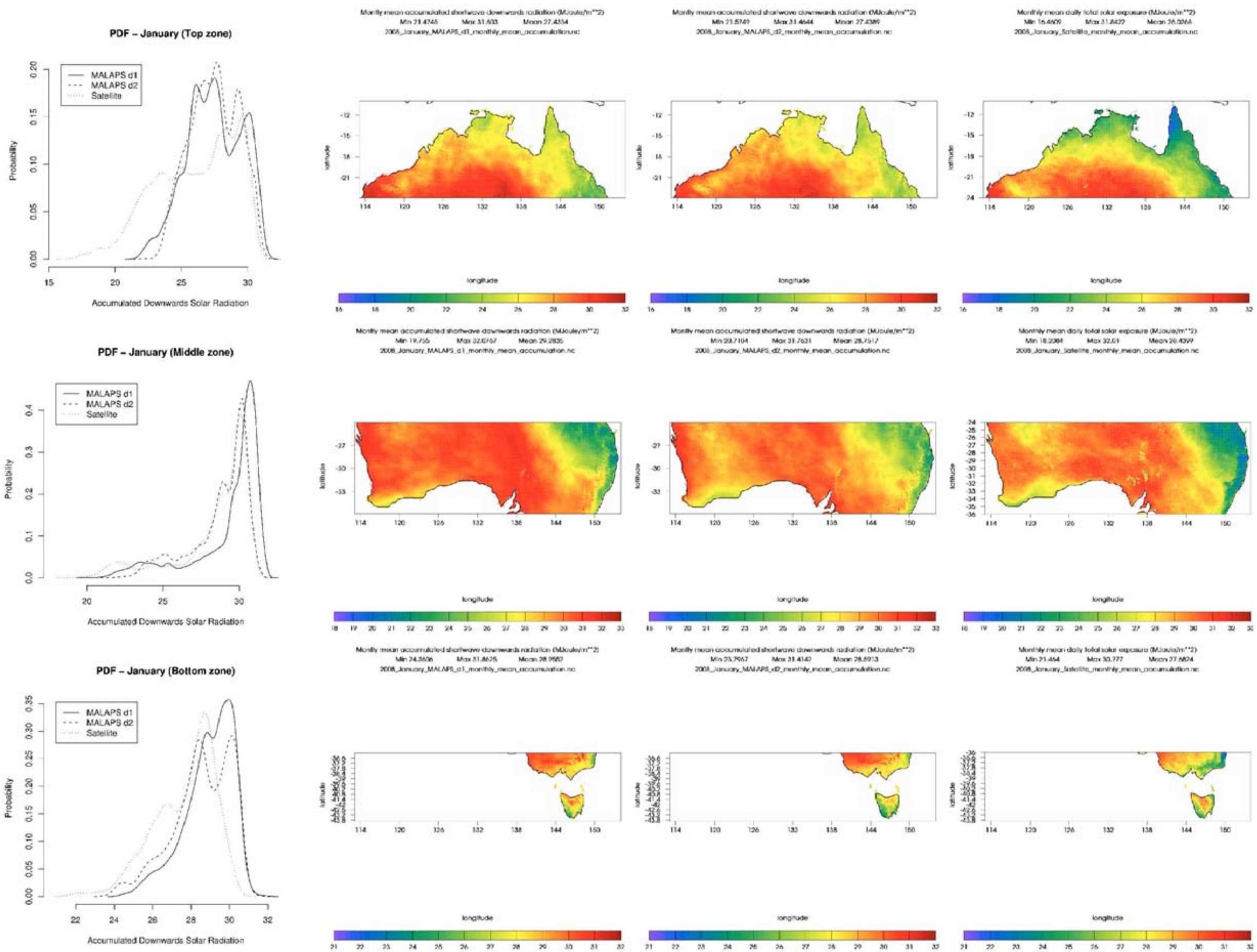

Fig. 10 Zonal spatial analysis of monthly averaged solar exposure for January. From L to R: PDF distributions for MALAPS and satellite data, colour plots for MALAPS 1st day forecast, MALAPS 2nd day forecast and satellite data

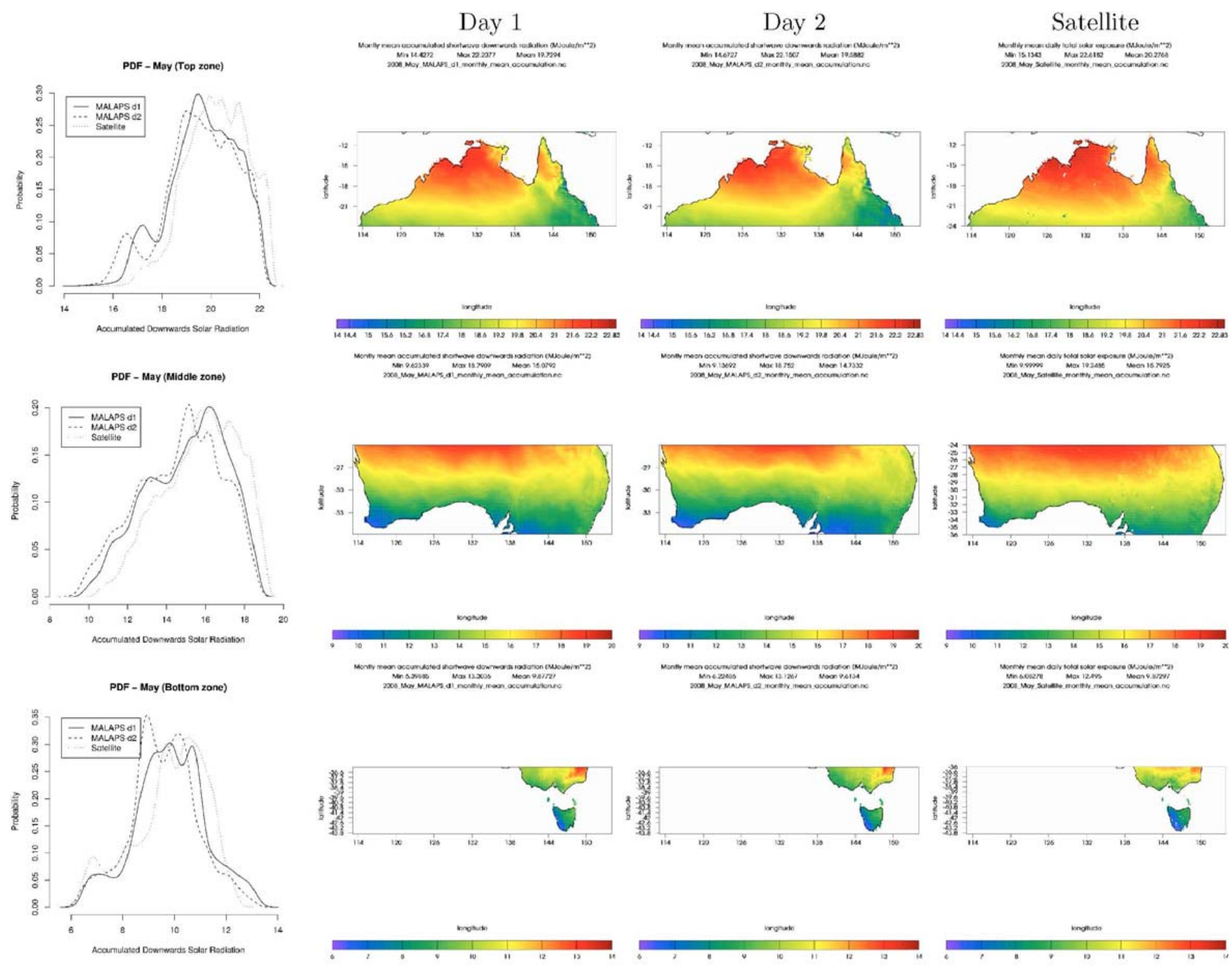

Fig. 11 Zonal spatial analysis of monthly averaged solar exposure for May. From L to R: PDF distributions for MALAPS and satellite data, colour plots for MALAPS 1st day forecast, MALAPS 2nd day forecast and satellite data

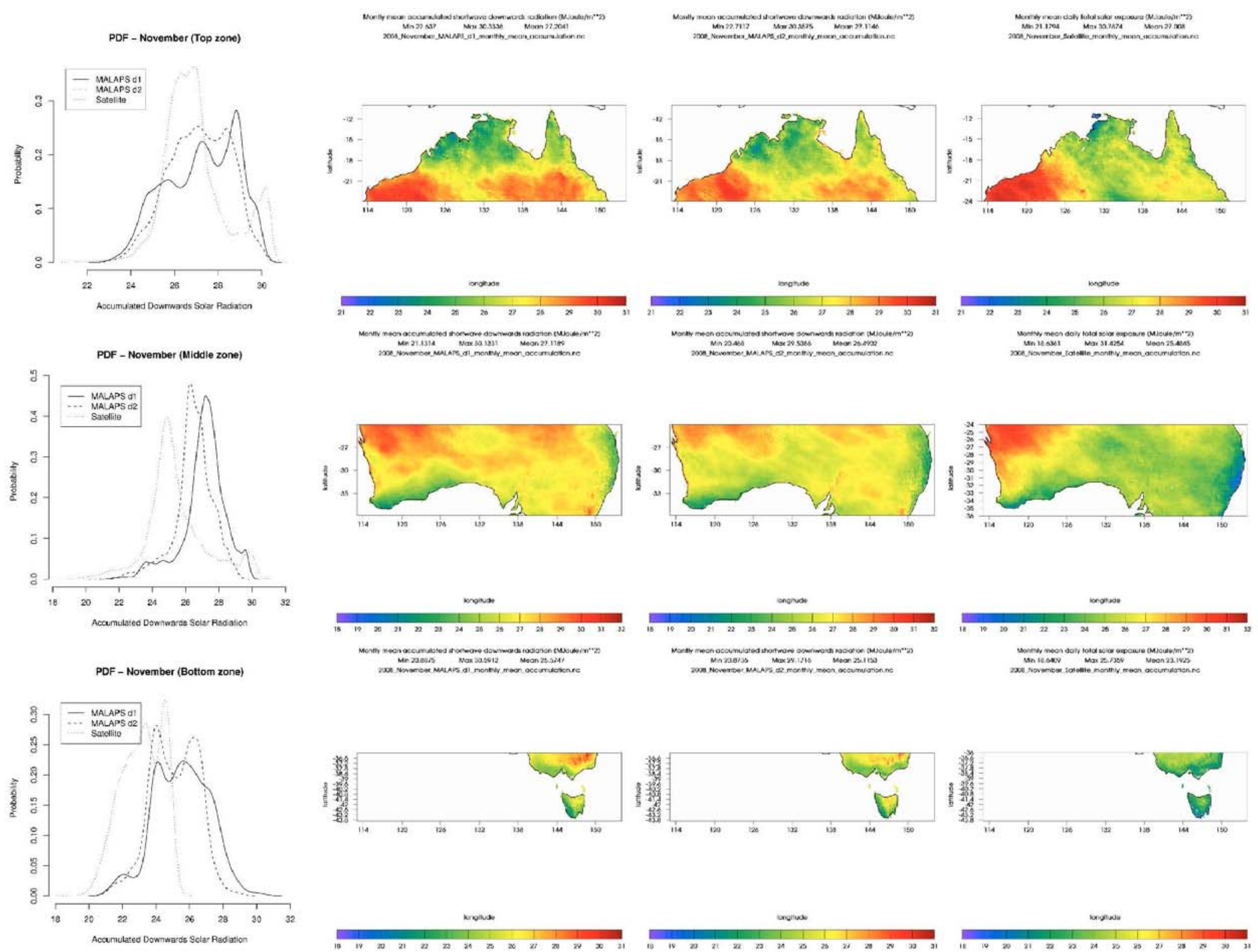

Fig. 12 Zonal spatial analysis of monthly averaged solar exposure for November. From L to R: PDF distributions for MALAPS and satellite data, colour plots for MALAPS 1st day forecast, MALAPS 2nd day forecast and satellite data

3.5 Daily results - spatial analysis

The spatial analysis from § 3.3 was repeated for specific days at each month to try to identify and highlight any common features between days which featured particularly good or bad agreement between the NWP and satellite results. Table 5 lists the days chosen for each month along with the computed differences in average solar exposure.

Table 5 *Average solar exposure across Australia at a specific day.*

Day	MALAPS		Satellite	Δ(Satellite -MALAPS)	
	1stday	2ndday		1stday	2ndday
January 18th	27.46	27.64	24.59	-2.87	-3.05
January 27th	28.10	27.84	27.98	-0.12	0.14
January 29th	28.39	27.72	28.88	0.49	1.16
January 30th	27.14	26.58	25.20	-1.94	-1.38
July 1st	14.89	14.70	15.59	0.70	0.89
July 5th	15.31	15.18	15.20	-0.11	0.02
July 19th	15.84	15.76	15.80	-0.04	0.04
July 22nd	15.45	15.57	14.51	-0.94	-1.06
November 4th	27.09	27.48	27.10	0.01	-0.38
November 7th	25.06	25.24	21.63	-3.43	-3.61
November 9th	29.41	28.90	29.57	0.16	0.67
November 10th	29.73	28.53	29.83	0.10	1.30

Spatial analysis of the selected days is shown in figures 13 to 16. This analysis gives examples of how accurately the NWP systems can predict cloud formations on a day-to-day basis, which is the most important aspect of being able to forecast solar exposure accurately. Taking a monthly average across all of Australia smoothes out any daily discrepancies between the NWP and satellite results. Therefore, the analysis of exposure colour plots and PDFs for specific days is an important step.

January 18th would be classified as a 'bad' day, in that there is a large discrepancy between the NWP and the satellite data. On January 18th, the eastern seaboard was dominated by a large band of cloud. While the NWP results show a reasonable amount of cloud in this region, there is insufficient cloud in the SE corner of Australia. Additionally, the cloud that is present doesn't provide enough attenuation of the solar exposure, i.e. it is too 'optically thin'.

January 27th provides an example of a ‘good’ day. In this instance, most of the continent is cloud free, although there is some lighter cloud in the tropical regions. Although the NWP results produce more cloud when compared to the satellite data, it is generally thinner which therefore produces a similar averaged exposure value. January 29th is another ‘good’ agreement day. In fact, it is one of the few days where the satellite data gives a larger averaged exposure value than the NWP results. As with the previous case, most of the continent is cloud free. Although the model produces more cloud than the satellite data, again it is too thin to have any real influence on the insolation.

The solar exposure patterns for January 30th show a similar trend to the previous day. The NWP forecast continues to produce too much cloud in the tropical regions. This day is classified as a ‘bad’ day compared to the previous day, mainly because the NWP forecast has failed to predict cloud associated with a large frontal cloud band over southern Australia.

July 1st provides an example of a ‘bad’ day in winter. This is an interesting case where once again, the satellite produces an averaged exposure greater than the NWP result. Additionally, the model insolation is much smaller over SE Australia implying that the model clouds are much thicker than those estimated by the satellite. Additionally, the NWP produces more cloud over the Queensland than observed by the satellite

July 5th shows a day of good agreement in winter. The southern half of the continent is dominated by cloud, and the NWP results show reasonable agreement with both the distribution and implied optical thickness when compared to the satellite data. However, there is a significant error in the satellite data for this day between the latitudes of -20° to -18° which is clearly a processing artifact. This sort of error in the satellite data is difficult to detect as it doesn’t show in a monthly exposure average, and the average daily exposure value is still sensible. This sort of error only becomes apparent with visual inspection.

July 19th is another example of good agreement. The PDFs from the NWP contain all the major features of the satellite distribution. However, the NWP produces slightly more cloud over central Australia. July 22nd is an example of a bad day. Once again, the clouds produced in the tropics over Queensland are too optically thin and create insufficient solar attenuation in this region. The NWP over predicts cloud attenuation in central Australia but this is insufficient to cancel the error due to the thicker cloud cover in Queensland in the daily mean.

November 4th is the first day selected from this month for analysis. The cloud distributions are very similar for both the NWP and satellite results, which in this instance is dominated by a large cloud band through central Australia. Once again, the NWP cloud is optically thinner than the satellite observations, providing less attenuation of solar exposure. This feature is noticeable in the enhancement of the left ‘tails’ of the PDFs.

November 7th is a continuation of the same synoptic feature, as this main cloud band crosses into SE Australia. At this point, the differences in optical thickness between the NWP and satellites become significant. There is much greater attenuation in radiation over SE Australia as the cloud has become thicker and more widespread. The NWP systems have failed to predict this increase in cloud. Note the large discrepancy in the shapes of the PDFs for this day.

November 9th and 10th provide examples of ‘good’ spring days as the continent is almost clear of cloud. In both instances, there is some cloud distributed through the tropics and along the coast of Queensland, with some isolated cloud in SE Australia. The NWP provides a good estimate of the cloud distribution and thickness, as can be seen by the by the similarity in the PDFs. For the 2nd-day forecast, the NWP predicted a large cloud mass forming off the Western

Australian coast near Geralton, but this failed to materialize. One important factor to note is an error in the satellite data over central NSW and Queensland. Artifacts of the processing are again apparent here, showing sharp discontinuities in the exposure field. These errors are difficult to detect without visual inspection.

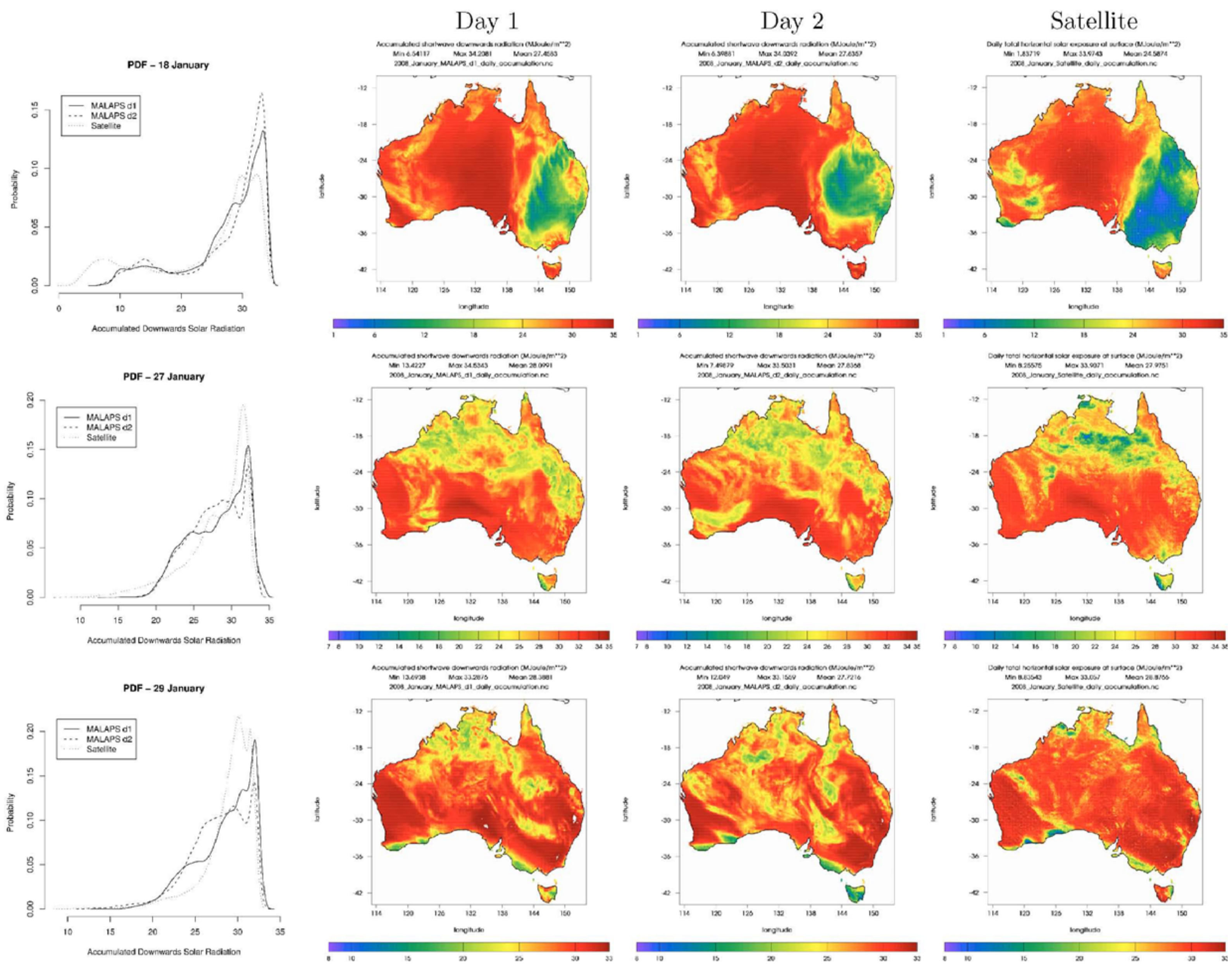

Fig. 13 Spatial analysis of daily solar exposure for January 18 (top), January 27 (middle) and January 29 (bottom). From L to R: PDF distributions for MALAPS and satellite data, colour plots for MALAPS 1st day forecast, MALAPS 2nd day forecast and satellite data

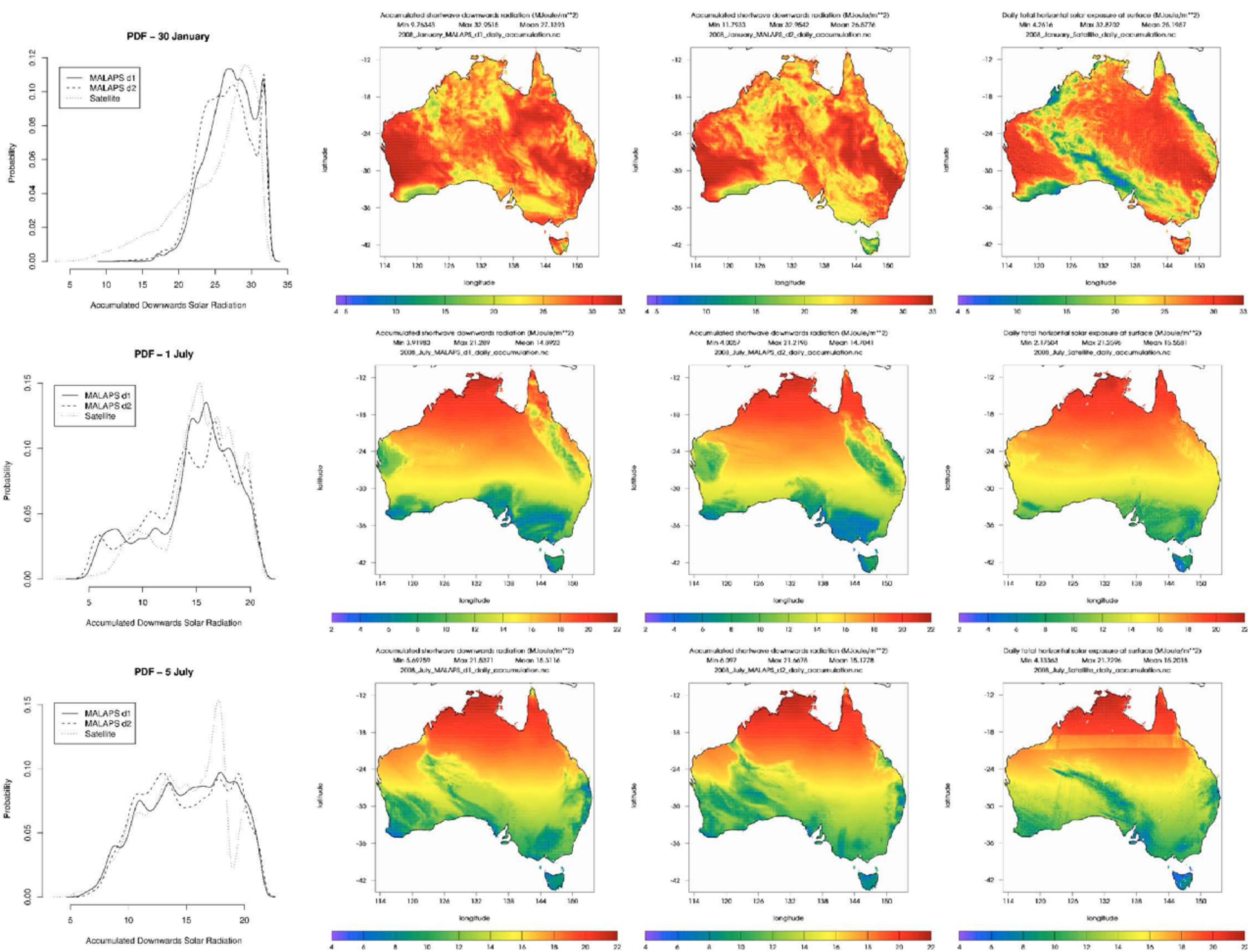

Fig. 14 Spatial analysis of daily solar exposure for January 30 (top), July 1 (middle) and July 5 (bottom). From L to R: PDF distributions for MALAPS and satellite data, colour plots for MALAPS 1st day forecast, MALAPS 2nd day forecast and satellite data

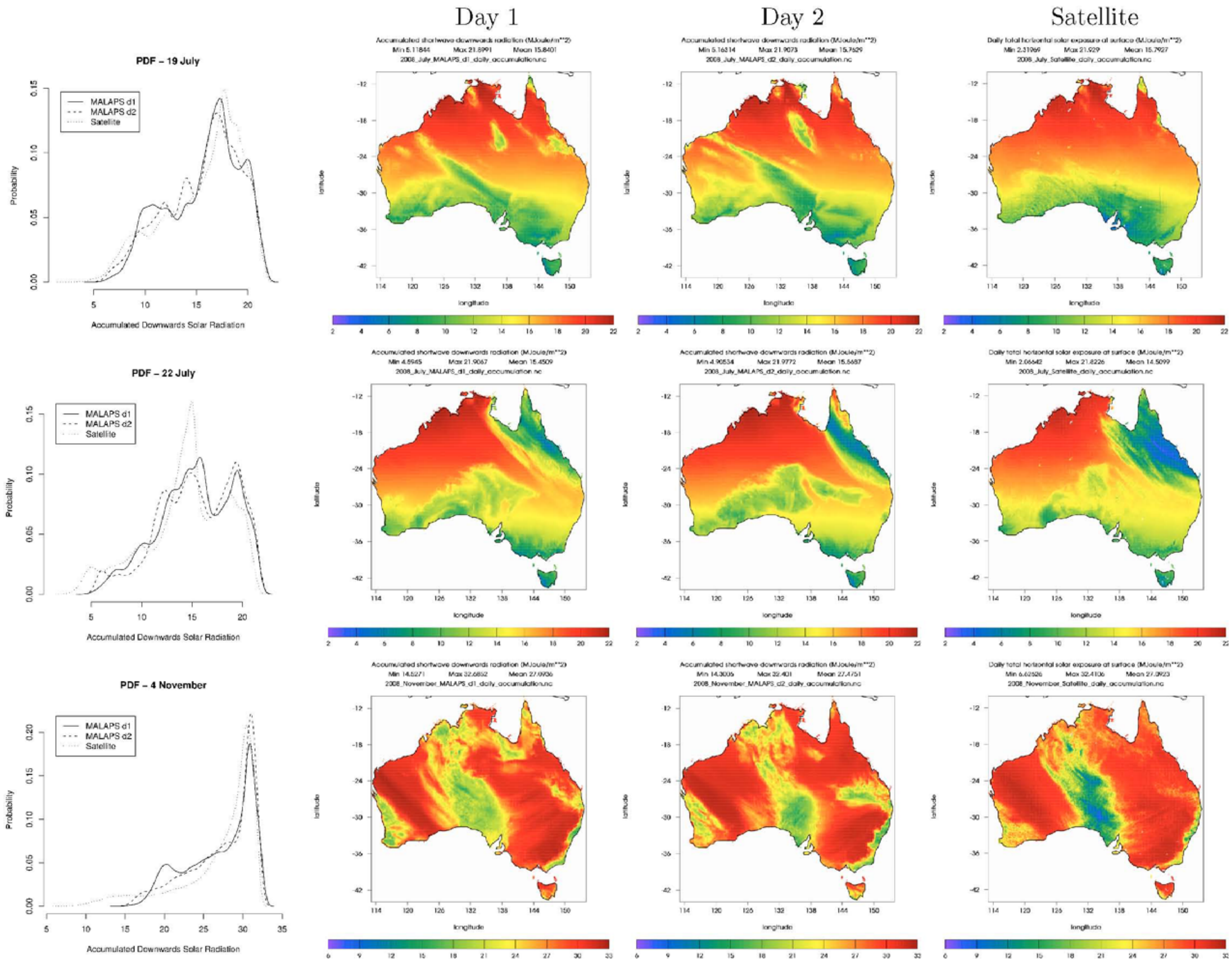

Fig. 15 Spatial analysis of daily solar exposure for July 19 (top), July 22 (middle) and November 4 (bottom). From L to R: PDF distributions for MALAPS and satellite data, colour plots for MALAPS 1st day forecast, MALAPS 2nd day forecast and satellite data

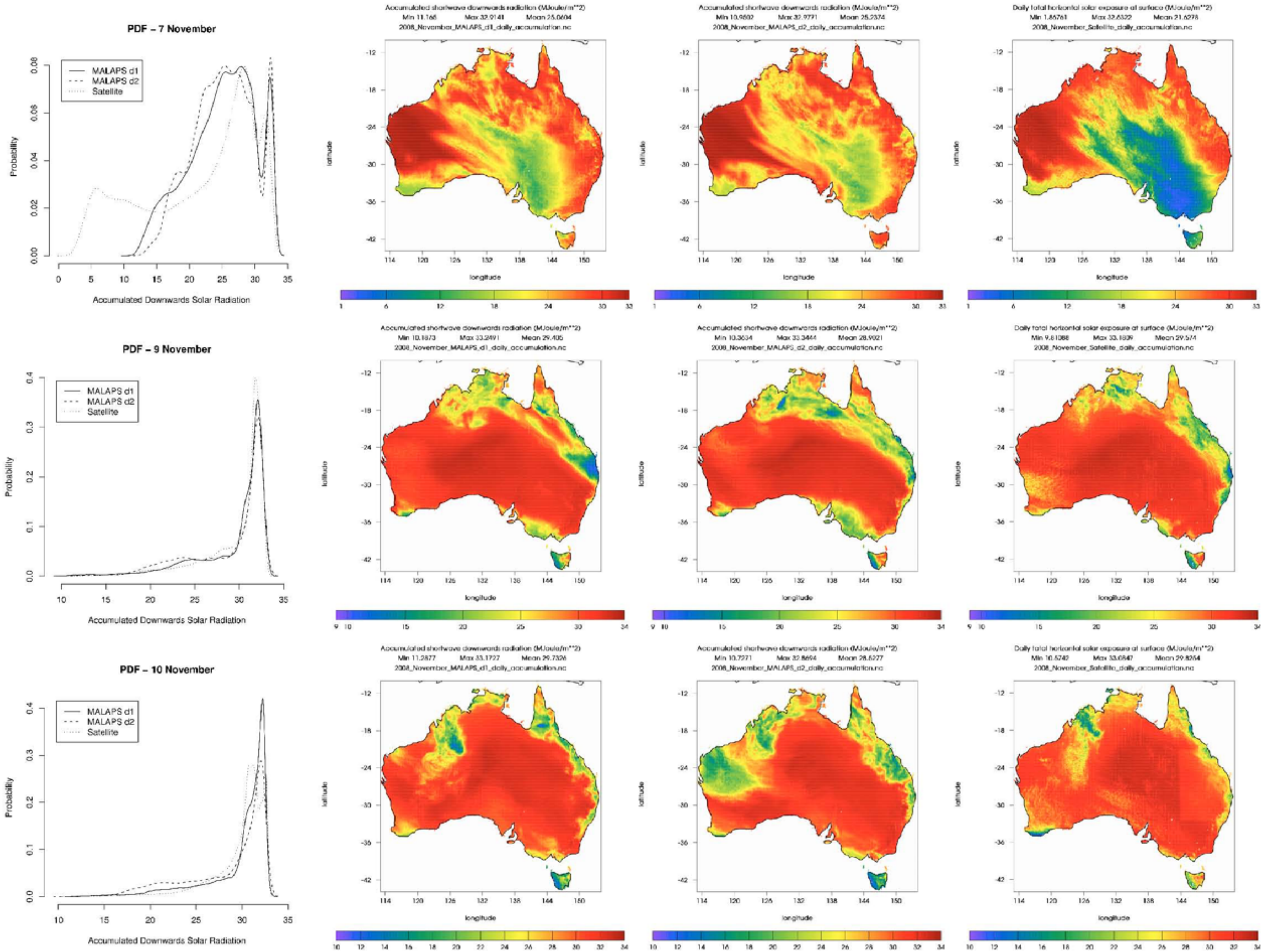

Fig. 16 Spatial analysis of daily solar exposure for November 7 (top), November 9 (middle) and November 10 (bottom). From L to R: PDF distributions for MALAPS and satellite data, colour plots for MALAPS 1st day forecast, MALAPS 2nd day forecast and satellite data

3.6 Section summary

This section presented solar exposure predictions over the entire Australian continent produced by the Bureau's NWP models. These were compared to the equivalent satellite measurements. Additional analysis was performed by constructing Probability Density Functions (PDFs) for the solar exposure plots. The PDFs show the relative amount of each value of exposure present over Australia for a given day (or month).

Using colour plots and PDFs of exposure showed that the NWP models systematically predict too much exposure in the tropics of Australia. This problem is mainly confined to the summer months. It is hypothesized that this over prediction of exposure is caused by the NWP algorithm treating the clouds present in this region as too transparent to incoming solar irradiance, i.e. they are too optically-thin. These discrepancies in the poor prediction of minimum values of exposure were also observed along the Great Dividing Range and in south-eastern Australia. These systematic errors create some opportunity for a bias correction.

The NWP models showed good agreement in the mid-latitude zones between -36.0°S to -24.0°S for most of the 2008 Calendar year.

4 DISCUSSION - NWP VS. SATELLITE

This section presents some physical mechanisms to explain the observed behaviour between the NWP models and the satellite data.

The analysis reveals that the most significant difference between the NWP forecast and satellite observations is the value of minimum solar exposure for any given day. This discrepancy is related to cloud formation; specifically forecast cloud features have insufficient cloud fraction or do not interact strongly enough with the radiation passing through it. The effect of the cloud on the radiation passing through it is determined by its physical thickness as well as the radiative properties of the cloud particles. The product of these is known as the cloud's optical depth. Larger optical depths imply stronger cloud effects on the radiation stream. Low optical depths have minimal effect on the radiation stream.

Generally, the NWP clouds are too 'optically-thin', i.e. they don't provide enough attenuation of the solar irradiance. These discrepancies were most noticeable over the Alps and tropics. The problems in SE Australia were particularly evident in the zonal analysis of the monthly averaged solar radiation.

The NWP system generally struggles to predict accurate exposure along the coast of Queensland.

Based on these observations and the known systematic errors in the NWP model formulation, it is hypothesized that most of the errors in tropical regions are due to an inability to correctly simulate convective cloud. In most tropical regions, local convective clouds are often produced locally i.e. they are not part of larger scale cloud bands and weather systems. Instead, they occur where the strong heating at the equatorial latitudes causes moist tropical air to rise and cool, triggering convection and creating optically thick convective clouds which often reach up to the tropopause.

Additionally, those clouds created near the Alps and along the Great Dividing Range are strongly influenced by geographical features. The presence of the mountains causes moist air to rise via orographic lifting, which in turn cools the moist air and creates clouds.

In order to test the validity of these hypotheses, the synoptic conditions for the days considered need to be analysed. Additionally, both model and satellite exposure data must be verified against ground-based measurements to check that the assumptions about cloud properties and the strength of the interaction with the radiation are correct.

4.1 Synoptic analysis

Synoptic analysis of the weather over Australia for selected days in January is shown in fig. 17. Only the MALAPS 1st-day forecast is shown, as this would be expected to give the most accurate forecast cloud field. For all of these days, large areas of low pressure exist over much of the northern half of the continent. This is a typical wet-season weather pattern.

January 18th featured a large high pressure system in the Tasman Sea which directed strong onshore easterly winds over the coast of Queensland and New South Wales. The low pressure system centred in the Northern Territory helped draw moist tropical air towards NSW as well. The combination of these two flows created heavy cloud coverage over most of Eastern Australia. The MALAPS cloud forecast provided a reasonable estimate of the cloud coverage over the continent, including the large cloud band across the eastern states as well as the cloud caused by a trough over Western Australia. However the optical thickness of the forecast cloud is insufficient to provide enough solar attenuation to match the satellite estimate.

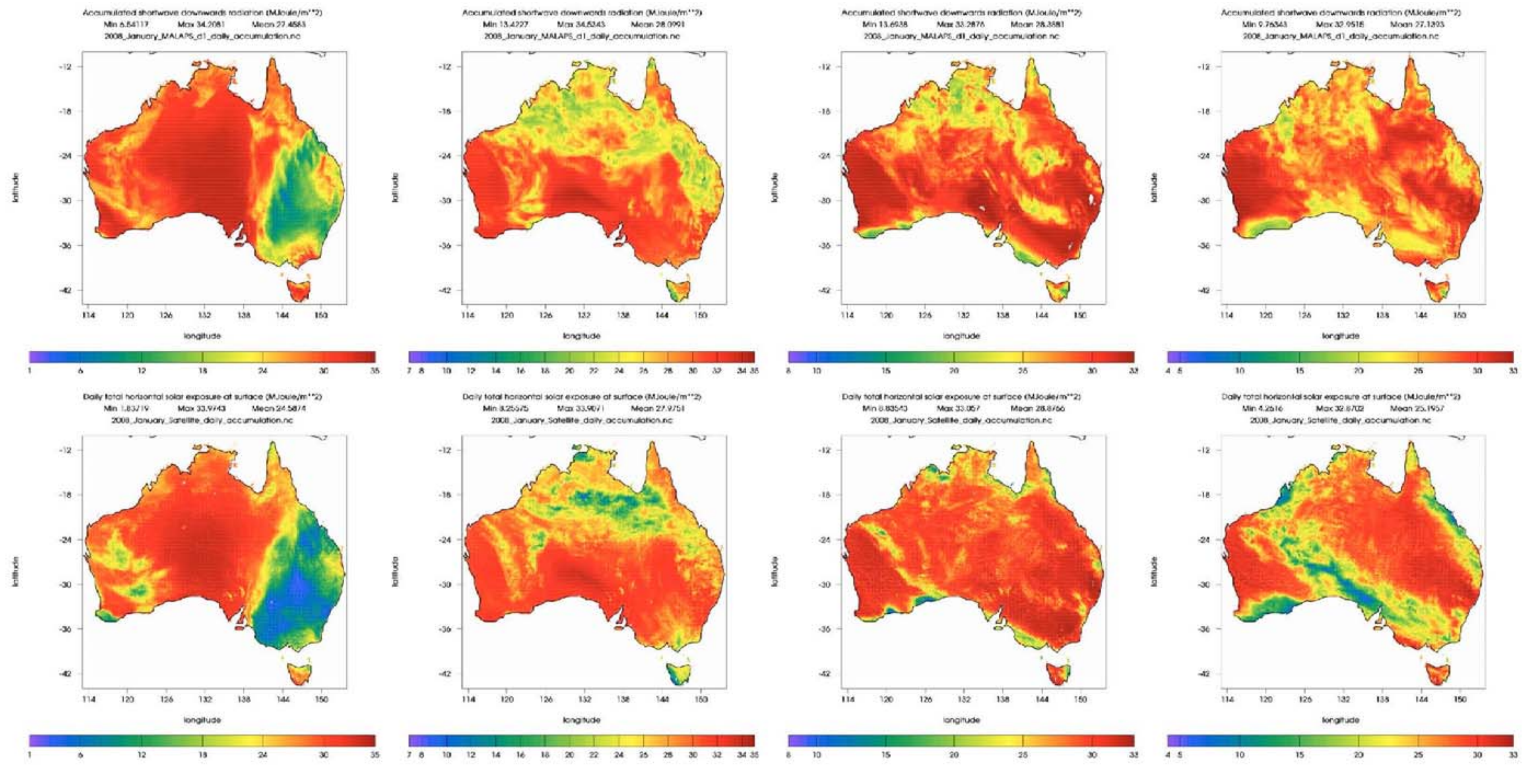

Fig. 17 Synoptic analysis for various days (top), plotted against solar exposure for the MALAPS 1st Day forecast (middle) and satellite data (bottom). From L to R : January 18, January 27, January 29 and January 30.

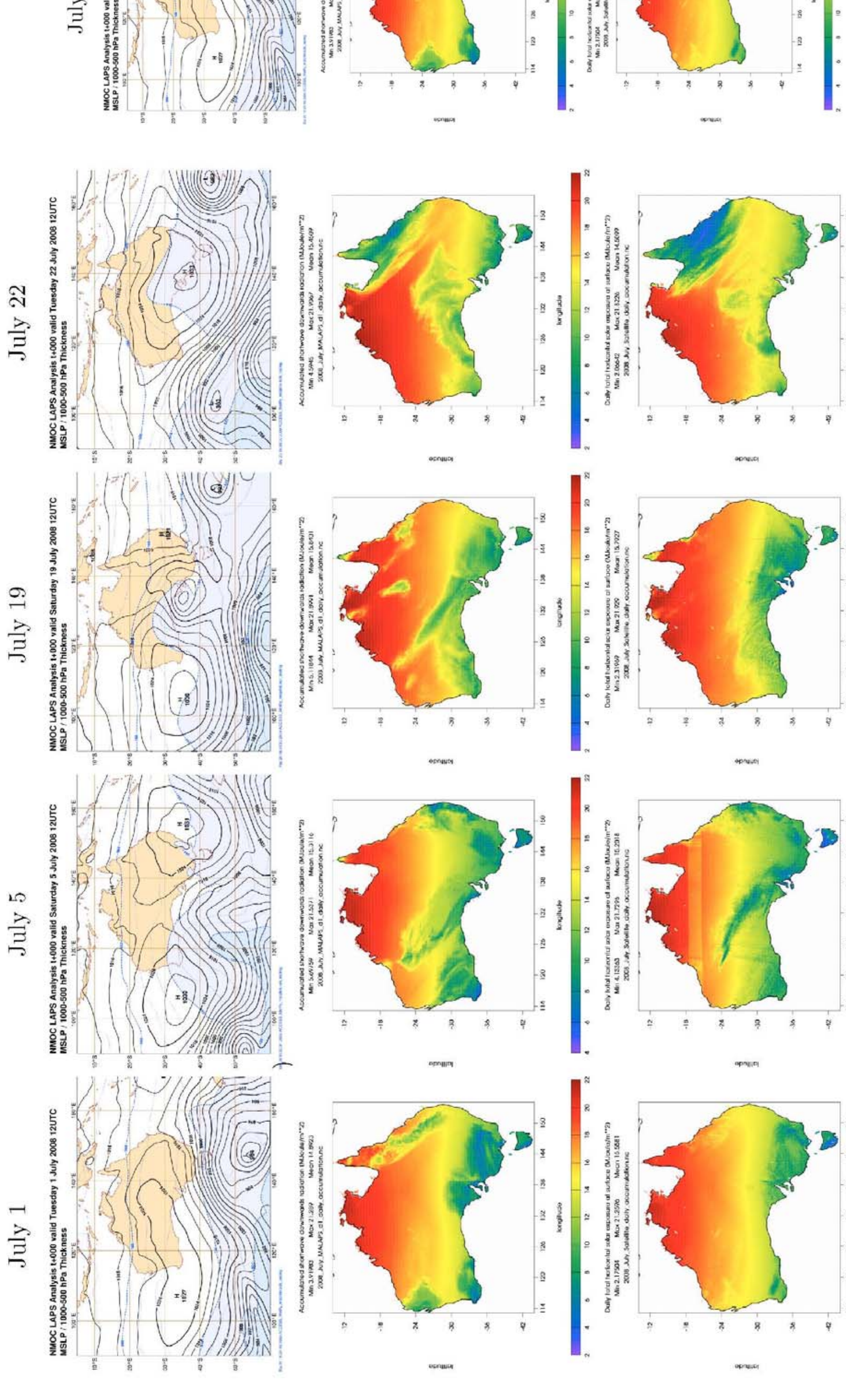

Fig. 18 Synoptic analysis for various days (top), plotted against solar exposure for the MALAPS 1st Day forecast (middle) and satellite data (bottom). From L to R : July 1, July 5, July 19 and July 22.

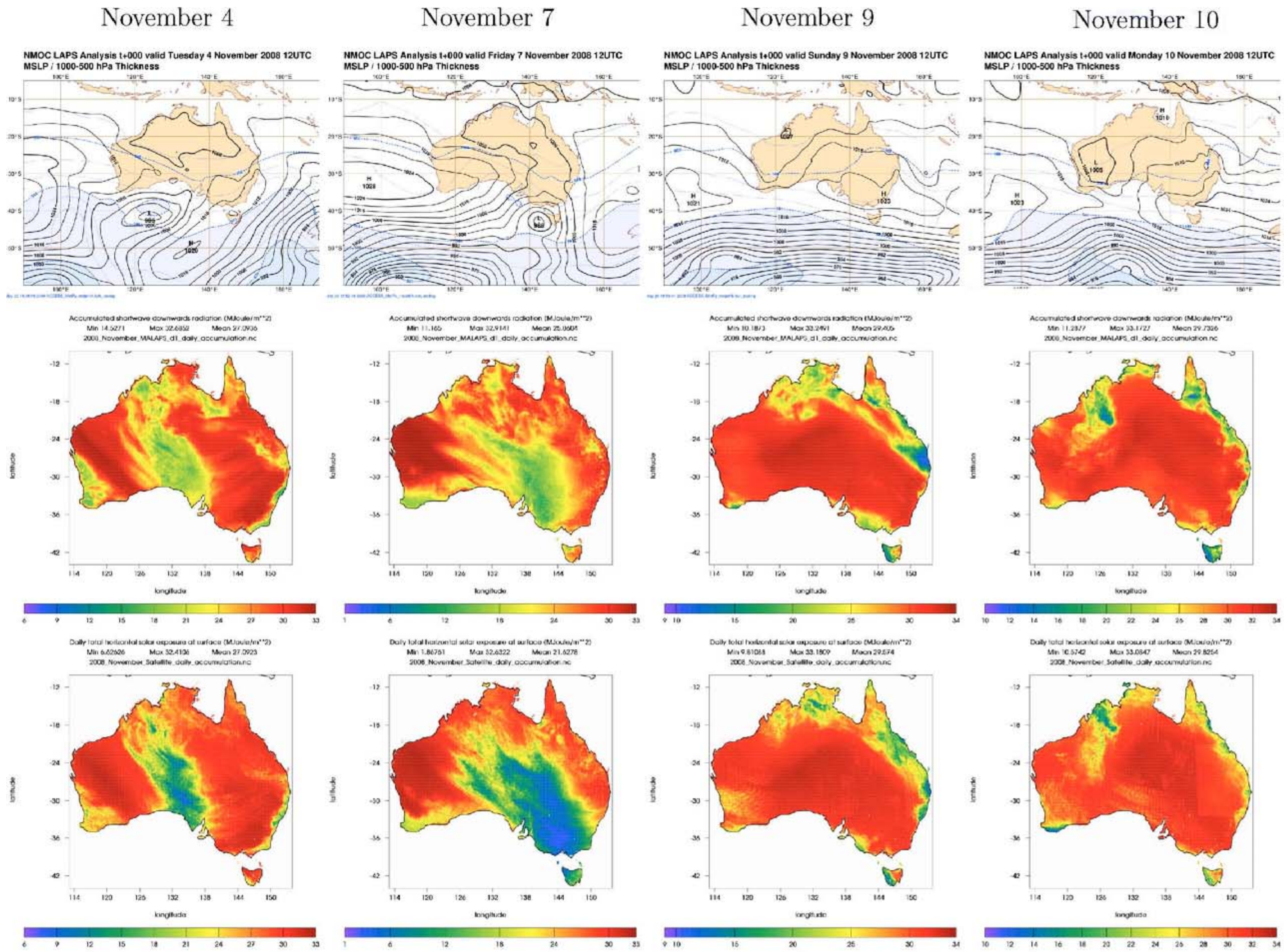

Fig. 19 Synoptic analysis for various days (top), plotted against solar exposure for the MALAPS 1st Day forecast (middle) and satellite data (bottom). From L to R : November 4, November 7, November 9 and November 10.

For January 27th, a ridge of high pressure across the Bight has kept southern Australia mostly cloud free. The low pressure system centred near Broome would create calm conditions throughout the tropics. The MALAPS forecast cloud is more extensive than was observed by the satellite. However, as this cloud was generally thinner than the satellite estimates, the overall agreement between the NWP and satellite for this day is very good. For the January 29th, the MALAPS forecast is very similar across the north of the continent. Additionally, a weak front is predicted to produce cloud across the southern coastal areas. The satellite results show that much of the cloud that was present on the day before in the tropics has now dispersed, although the presence of frontal cloud along the southern coastline show good agreement with the forecast.

On the following day a mid-level cloud band has developed in the Bight. This is due to the intensification of the low which has now moved south of Carnarvon. Combined with the movement of the high pressure system off Perth further into the Bight, this has created conditions favourable to cloud formation over southern Australia. The NWP has missed this cloud formation over the southern half of the continent although it is still producing too much cloud in the tropics.

Synoptic analysis of the weather patterns over Australia for selected days in July is shown in fig. 18. These charts show typical winter patterns, which feature high pressure systems sitting further north than in the summer, allowing low pressure troughs and cut-off lows to pass over the southern half of the continent.

On July 1st, a large high pressure system over Australia kept most of the continent cloud free. However, this system directed cold westerly winds over south-east Australia, creating some cloud in this area. For this day the NWP forecast created more cloud cover over southeast Australia than the satellite estimates. The model also created much heavier cloud along the Queensland coast, as well as across the Gascoyne region near Canarvon.

The synoptic chart for July 5th shows a large low-pressure trough extending into the Bight. In this case, the model predicted slightly more cloud coverage across South Australia compared to the satellite. However, in this case the predicted cloud is thinner compared to the satellite estimate leading to overestimated surface insolation.

July 19th featured a low-pressure system that pooled large amounts of cold air near Adelaide. These conditions again create large frontal cloud bands over southern Australia. The trend between the NWP and satellite data was the same as for July 5th, in that the NWP forecast predicted greater cloud coverage.

The weather pattern for July 22nd is dominated by a large high-pressure system situated over south-east Australia. This creates strong on-shore easterly winds over the coast of Queensland. In this instance the NWP forecast produces a good estimate of cloud coverage, again, however the cloud itself is too optically thin compared to the satellite estimate. This reinforces the trends observed during January, in that the NWP will produce cloud that is too optically thin in tropical regions. This is most likely due to the way that convective cloud is incorporated into the model's radiative transfer calculations and is expected to be greatly improved in the ACCESS system.

Synoptic analysis for selected days in November is shown in fig. 19. November 4th shows a large low-pressure system situated south of the Bight. This low-pressure system has created a large cloud band associated with a trough over South Australia. The NWP forecast shows an excellent prediction of cloud coverage, however the implied cloud optical thickness is again too low when compared to the satellite estimate.

The low pressure system continued to intensify and move eastwards, creating more cloud coverage. The results for the 7th of November are identical to the 4th of November, in that the NWP forecast shows good prediction of cloud coverage but poor estimates of cloud attenuation relative to the satellite estimates.

The following days saw the southern half of the country dominated by a large ridge of high pressure, which kept most of the continent cloud free. The charts for November 9th and 10th show scattered clouds over the tropics and along the Queensland coast. For both of these days, the NWP forecast and satellite data show good agreement.

The synoptic analysis has supported some of the hypothesis proposed in the previous sections. The NWP continually over predicts cloud coverage in the tropical regions during summer. These events are shown to occur on days with light winds (i.e. there are small pressure changes across the north of the continent). On these days, there is no cloud created by passing fronts or storms, so all cloud is created mainly by local processes (e.g. convection). On days when there are larger changes in pressure (e.g. offshore easterly winds) the NWP forecast is able to better predict cloud coverage. However, the prediction of cloud optical thickness still remains an issue.

The prediction of cloud bands across southern Australia is inconsistent. For the selected days in July, the NWP forecast predicts too much cloud coverage. However in November, the NWP prediction of cloud coverage is better. Again, the issue of cloud thickness and optical depth is a separate source of error.

4.2 Section summary

Monthly analysis of the NWP results for the entire year has shown that the cloud schemes are unable to accurately forecast cloud in the tropics during the summer months. Synoptic analysis suggests that these discrepancies are worse in the summer when monsoon conditions in the tropics exist, resulting in cloud generation that is governed by local convective processes. However, the performance of the NWP over the southern half of the continent has been shown to be quite good.

Analysis of the winter months suggests that the NWP model can predict the movement of large cloud bands across the continent generated by cold fronts and troughs relatively well.

However, while the forecast of cloud coverage may be accurate, the predicted clouds are still too transparent to solar irradiance when compared to the satellite estimates. These consistent errors in predicted cloud thickness gives possible scope for a bias correction.

5 RESULTS – GROUND BASED OBSERVATIONS

Recall from §1.3 that the satellite infers values of surface solar exposure; it doesn't measure it directly. In order to validate the NWP models against known surface exposure quantities, the use of ground-based measurements is required.

This section of the report validates the NWP results against the Bureau's radiation monitoring network. Monthly averages of daily surface exposure for each site are presented, along with time series for accumulated exposure for selected months at each site. Finally, hourly analysis for selected days at various sites is presented. The hourly analysis allows the observed direct and diffuse exposure and the observed cloud fields to be compared against the NWP forecasts for exposure and cloud coverage. This detailed analysis should make it possible to accurately test the hypothesis proposed earlier in § 4, namely the current NWP algorithms treat high cloud as too transparent to incoming solar irradiance.

5.1 Monthly results

Data for the ground based solar exposures were obtained from the sites listed in tables 6 and 7 At the time this report was completed, data was available from the Bureau's archives for the first ten months of 2008 (there is some delay due to data processing and quality control).

Comparison between the site data and gridded NWP and satellite data was achieved by extracting the NWP and satellite values at the closest grid point to each site. This is a crude form of 'downscaling' and more mathematically rigorous methods exist which give more accurate answers. However, the closest-point method is satisfactory for this preliminary report.

Table 6 shows monthly averaged exposure values at every site, along with the differences between the satellite and NWP data and the site data. The table show that the accuracy of both the satellite and model data (compared to the site observations) vary greatly between different sites and different months. The results show that satellite data gives the worst estimates of solar exposure in Melbourne. Indeed, the averaged NWP results are usually closer to the site observations than the satellite data at this site. The satellite data is not totally independent of the surface data, as the satellite model is 'tuned' against the ground observations.

Darwin and Rockhampton are both located in the tropics, and they too feature larger errors between the satellite data and site observations. Table 6 also highlights the inability of the NWP systems to accurately predict solar exposure in the tropics during the summer. However, outside of the summer months, the averaged NWP results are often more accurate than the satellite.

Although Broome is also located in the tropical latitudes, its position on the west coast of Australia results in it experiencing different cloud patterns. At this site, the satellite data shows very good agreement with ground-based site observations. The NWP results give similar performance to that observed in Darwin and Rockhampton, i.e. poor during summer, but excellent for autumn and winter.

Table 6 *Monthly averaged exposure values for NWP and satellite data extracted at various sites in Australia.*

Data for site Alice Springs							
Month	MALAPS		Satellite	Site	Δ		
	1stday	2ndday			1stday	2ndday	Satellite
January	31.37	31.39	30.37	29.33	2.04	2.05	1.04
February	27.55	27.85	26.99	26.6	0.95	1.25	0.39
March	26.42	25.94	25.25	22.4	4.02	3.54	2.85
April	22.66	22.65	22.93	22.01	0.65	0.64	0.92
May	18.92	18.88	19.35	16.79	2.13	2.09	2.56
June	16.47	16.24	16	14.34	2.14	1.9	1.66
July	17.86	17.56	17.48	17.24	0.62	0.32	0.24
August	20.01	19.97	19.26	19.06	0.94	0.91	0.19
September	24.24	23.91	23.28	23.14	1.1	0.78	0.14
October	28.04	27.53	27.59	26.55	1.5	0.98	1.04
Data for site Darwin							
January	25.33	25.84	21.67	18.76	6.56	7.08	2.9
February	23.16	24.68	16.98	15.14	8.02	9.53	1.84
March	23.53	24.66	24.26	20.32	3.21	4.34	3.93
April	24.52	24.52	25.06	23.06	1.46	1.46	2.01
May	21.77	21.49	22.31	20.77	1	0.72	1.54
June	19.93	19.67	20.17	18.86	1.07	0.82	1.32
July	21.02	20.93	21.42	20.2	0.82	0.73	1.22
August	22.88	22.69	22.72	20.29	2.59	2.4	2.43
September	24.3	26.21	24.59	22.26	2.05	3.95	2.33
October	25.56	27.35	25.94	22.73	2.84	4.63	3.22
Data for site Cape Grim							
January	29.03	26.98	29.93	28.04	0.99	-1.06	1.89
February	23.1	23.85	23.06	21.66	1.45	2.19	1.4
March	18.42	17.65	19.52	17.53	0.89	0.12	1.99
April	12.26	12.21	13.12	10.91	1.35	1.31	2.21
May	7.9	7.64	8.36	6.38	1.51	1.25	1.97
June	6.71	6.59	6.83	5.4	1.31	1.19	1.44
July	8.13	8.04	7.86	6.57	1.56	1.47	1.28
August	11.15	10.83	10.99	9.57	1.58	1.26	1.42
September	14.78	14.62	14.86	13.02	1.76	1.6	1.84
October	20.73	20.19	21.21	19.16	1.57	1.03	2.05
Data for site Wagga Wagga							
January	29.81	29.01	27.97	26.19	3.63	2.82	1.78
February	25.63	25.33	24.06	24.19	1.44	1.14	-0.13
March	22.66	21.87	21.55	20.99	1.67	0.87	0.55
April	16.59	16.68	16.48	15.2	1.39	1.48	1.28
May	11.92	11.52	12.36	10.75	1.18	0.78	1.61
June	9.34	9.35	9.38	7.59	1.75	1.77	1.79
July	10.19	10.37	9.78	7.77	2.42	2.59	2
August	14	14.24	12.34	11.24	2.75	3	1.09
September	21.2	21.01	19.69	19.7	1.5	1.31	-0.01
October	25.71	24.87	24.74	24.44	1.27	0.43	0.3

Table 7 *Monthly averaged exposure values for NWP and satellite data extracted at various sites in Australia (cont).*

Data for Broome							
Month	MALAPS		Satellite	Site	Δ		
	1stday	2ndday			1stday	2ndday	Satellite
January	27.82	27.71	25.07	24.68	3.14	3.02	0.38
February	25.23	25.68	20.24	18.63	6.6	7.05	1.61
March	24.14	24.18	23.86	23.06	1.08	1.12	0.8
April	22.7	22.78	23.69	22.25	0.45	0.53	1.44
May	20.68	20.65	21.01	19.65	1.03	1	1.36
June	18.11	18.23	17.97	16.91	1.19	1.32	1.05
July	20.04	20.2	19.74	19.21	0.83	0.99	0.53
August	21.81	22.17	22.22	0.001	21.81	22.17	22.22
September	24.78	25.29	25.19	22.8	1.98	2.48	2.39
October	26.72	27.1	27.96	25.81	0.91	1.29	2.15
Data for site Melbourne airport							
January	28.84	28.82	28.58	25.13	3.71	3.69	3.45
February	22.42	22.89	24.78	18.11	4.3	4.77	6.67
March	20.68	19.94	21.04	17.74	2.94	2.2	3.3
April	14.7	13.86	15.78	12.24	2.46	1.62	3.54
May	9.74	9.87	11.97	7.28	2.45	2.59	4.69
June	8.7	8.1	9.56	5.99	2.71	2.11	3.57
July	9.21	9.29	10.04	7.13	2.08	2.15	2.91
August	12.28	12.42	12.74	9.16	3.12	3.26	3.58
September	18.53	18.27	18.99	15.66	2.87	2.62	3.33
October	23.42	20.97	24.14	17.95	5.47	3.02	6.19
Data for site Rockhampton							
January	23.73	25.29	21.1	17.81	5.92	7.48	3.29
February	22.74	22.42	18.94	17.42	5.32	5	1.52
March	22.75	22.48	24	21.78	0.97	0.7	2.23
April	21.29	21.29	22.03	20.62	0.66	0.67	1.4
May	16.92	16.42	17.1	14.63	2.29	1.79	2.47
June	14.31	13.45	15.04	13.26	1.05	0.19	1.78
July	14.94	14.48	13.94	12.41	2.52	2.07	1.53
August	19.78	20.26	19.02	18.54	1.25	1.72	0.48
September	22.13	22.83	21.1	19.69	2.44	3.14	1.41
October	24.45	25.71	24.95	23.31	1.13	2.39	1.64
Data for site Adelaide							
January	31.06	30.2	31.44	30.34	0.72	-0.14	1.1
February	25.96	26.12	24.53	24.61	1.35	1.5	-0.08
March	21.44	21.09	22.87	21.13	0.31	-0.04	1.74
April	14.61	14.37	16.31	14.03	0.58	0.34	2.28
May	10.84	10.14	12.45	10.81	0.03	-0.67	1.64
June	9.43	8.97	9.67	7.68	1.76	1.3	2
July	9.73	9.55	10.39	8.56	1.17	0.99	1.83
August	12.2	12.57	14.05	11.91	0.29	0.66	2.14
September	19.09	18.68	20.06	18.62	0.47	0.06	1.44
October	23.13	22.54	24.26	22.73	0.4	-0.19	1.53

The sites at Alice Springs, Wagga Wagga and Adelaide show similar differences between the satellite data and site observations. All three sites show large monthly fluctuations in errors between the satellite and site results. The differences between the NWP and site observations also show large month-to-month variation. The NWP performs slightly worse than the satellite data at Alice Springs and Wagga Wagga, and arguably slightly better at Adelaide.

The results for Cape Grim are slightly worse than these three sites, with both the NWP and satellite data producing errors of similar magnitude. In general, both the satellites and NWP produce better results at the mid latitudes. The two southerly stations (Melbourne, Cape Grim) and two tropical stations (Darwin, Rockhampton) produce the largest errors for both.

One interesting feature is how much better the satellite and NWP systems perform predicting solar exposure for Adelaide when compared to Melbourne. Additionally, the large differences in accuracy of the satellite data for Broome when compared to Darwin and Rockhampton are also interesting. This is probably related to the cloud climatologies at these three sites. Even though all three sites are at similar latitudes, Broome has a much drier climate and therefore it has a much higher ratio of clear-sky days.

5.2 Daily results

Figure 20 shows the results of daily solar exposure at each selected site for January. The NWP data from the 2nd-day MALAPS forecast is shown. Note that at several sites there is no available site data for January 1st. The plots provide further evidence to support the conclusions made based on the monthly averaged exposures, namely that the NWP gives good estimates of local solar exposure values at the mid-latitudes.

The results for Adelaide, Alice Springs and Wagga Wagga show that the satellite data has excellent agreement when compared to the site-based observation. The NWP results for these sites are generally very good, and show the ability to predict variation in solar exposure up to two days in advance. At Adelaide, there are some days where the NWP provides too much solar attenuation, although at Alice Springs and Wagga the NWP results gives too little solar attenuation on days with large amounts of cloud cover.

At higher latitudes, the results for Darwin and Rockhampton show much greater variability in solar exposure. There are larger differences between the satellite and site-based data, with the satellite results giving larger values of daily solar exposure compared to the site data. The magnitude of the MALAPS results are generally larger again than the satellite results, resulting in significant errors between the NWP and site results. The forecast magnitude of exposure at these stations is consistent with the earlier analysis which shows that the cloud produced by the NWP systems in the tropics is too optically thin. However, the results show that the NWP system is able to forecast qualitatively the changes in solar exposure quite well. Good examples are the observed from Jan 1st -15th at Darwin, and January 7th -20th at Rockhampton. Over these periods, there is almost a constant offset between the model data and site data.

The results for Melbourne show large discrepancies between the satellite data, which often over predicts the site-based observations, particularly in the second half of the month. During the period of 11th -16th of January, the NWP forecast provides a better estimate of solar exposure than the satellite data.

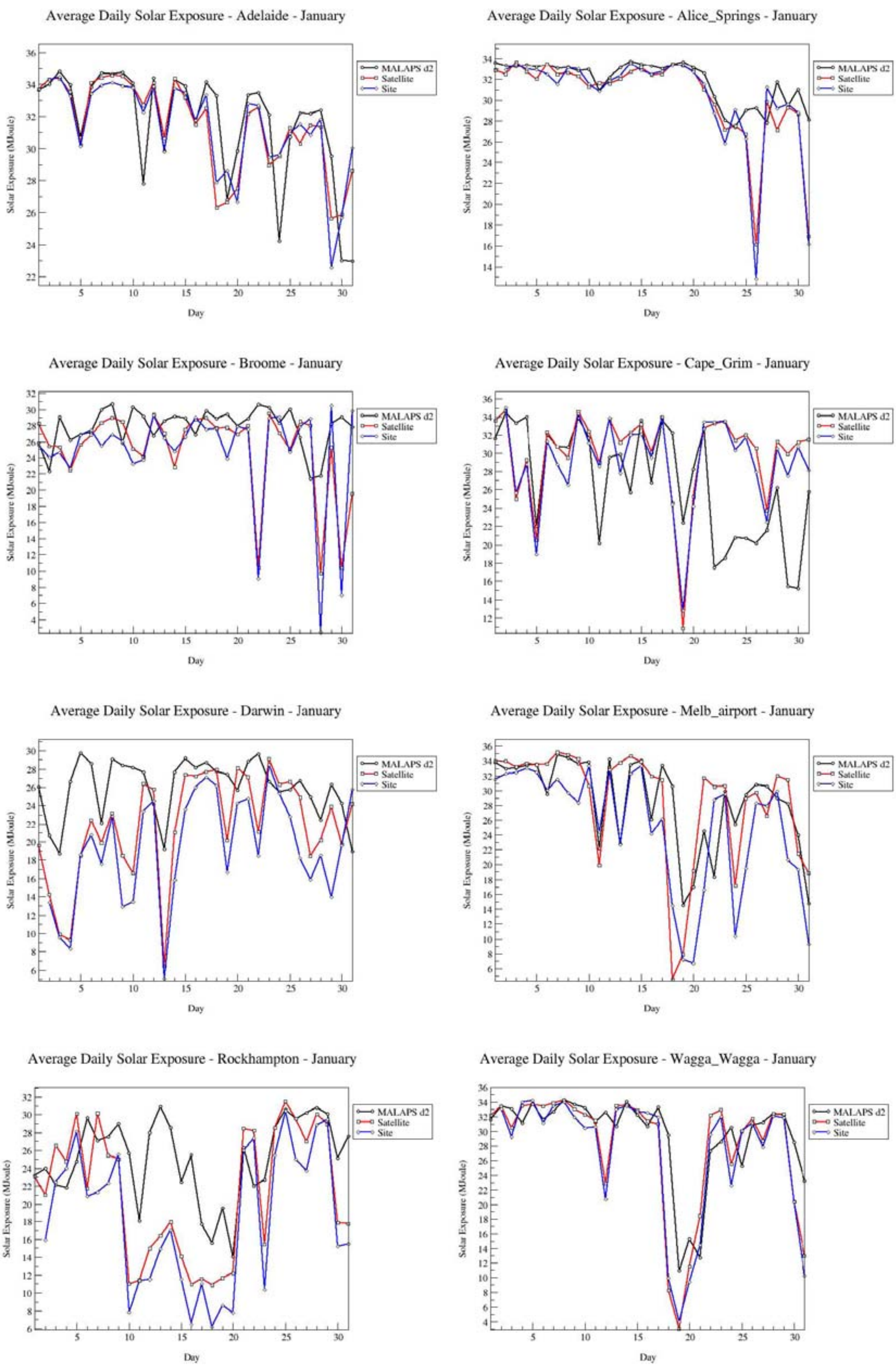

Fig. 20 Plots of daily solar exposure for January at selected sites within Australia. The MALAPS 2nd-day forecast is shown, along with the satellite estimates. Note that the y-axis is different at each site

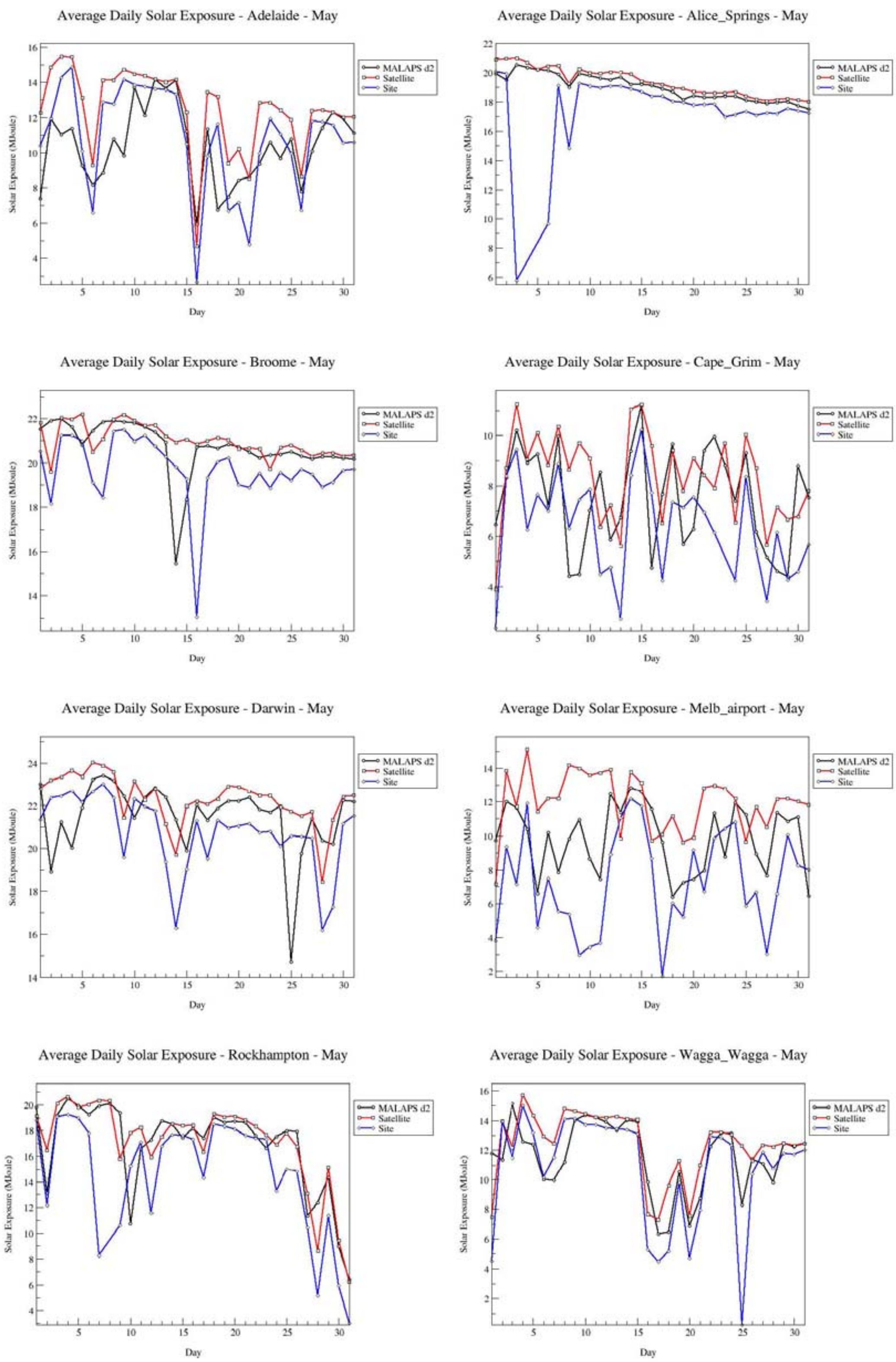

Fig. 21 Plots of daily solar exposure for May at selected sites within Australia. The MALAPS 2nd-day forecast is shown along with the satellite estimates. Note the y-axis is different at each site.

The trends for Cape Grim are fairly unique. For this site, the satellite and site-data show very good agreement, however the 2nd-day MALAPS forecast often under predicts the magnitude of the daily solar exposure. This is very evident over the last third of the month.

Figure 21 shows the daily solar values for the month of May. As the season moves from summer to winter, the performance of the NWP and satellite systems relative to the ground-based site observations changes significantly.

Examining the mid-latitude sites of Adelaide, Alice Springs and Wagga Wagga shows that the NWP data gives better estimates of solar exposure for most days in May. The satellite data overestimates the magnitude of the solar exposure in most instances. This could be due to the use of bias corrections extrapolated from the previous year. For Alice Springs, this month was dominated by clear-sky conditions with little to no major attenuation in solar exposure. Except for the 8th May, the site-based exposure vales show no major attenuation (it is assumed that the site exposure values from the 3rd-6th of May are. The reduction in daily solar exposure over the month is quite evident, as the sun is now lower in the sky as the winter solstice approaches. The Alice Springs results provide a striking example of how well the NWP system can predict solar exposure under clear-sky conditions.

The May results for Adelaide also show the trend for the satellite data to over predict solar insolation relative to the ground-based observational data. The NWP data provides worse agreement with the ground-based data for the first half of the month, but it gives better agreement for the latter part of the month. The MALAPS results for Wagga Wagga show even better agreement with the observations than the Adelaide results.

At higher latitudes, the NWP data still provides better estimates of solar exposure than the satellite data. At Broome and Darwin, the model has a few bad days where it misses the presence of major cloud formation (and associated attenuation) by a day or two, but the overall behaviour is still better than the satellite data, which often shows no attenuation around these dates. At Rockhampton, the performance of MALAPS and the satellite data is very similar (there is missing site data for the 8th of May).

At Melbourne, both MALAPS and satellite data show poor agreement with the large variability of the site data, although the NWP data is superior. This is reflected in the superior mean error for the 2nd-day MALAPS forecast when compared to the satellite error (see table 7). The trends at Cape Grim are again similar for those in Melbourne.

The trend for the MALAPS data to perform poorly at coastal locations can be explained by the models inability to cope with strong cloud gradients along the coast. Often sharp boundaries in cloud concentration can form along the coast due to differences in temperature and heating rate between the land and ocean. The nature of the discretization schemes used in NWP can make it difficult to represent these strong gradients without an excessively fine grid.

5.3 Hourly results

As mentioned previously in §2.3, the ground-based observations also record cloud fraction and cloud height at half-hourly intervals. The use of this data enables comparison with the cloud fields present in the NWP model at any particular site. This data allows the errors in solar radiation to be attributed to either

1. The NWP giving poor forecasts of cloud amounts,
2. The NWP giving poor computations of optical thickness for the clouds present,

or a combination of both factors.

5.3.1 Rockhampton - January 11th -15th

Figure 22 shows the daily solar exposure data at Rockhampton for January. Table 8 shows the values of accumulated exposure at Rockhampton for the NWP and site observations over the period January 11th-15th. As noted previously, these days are an example of the NWP

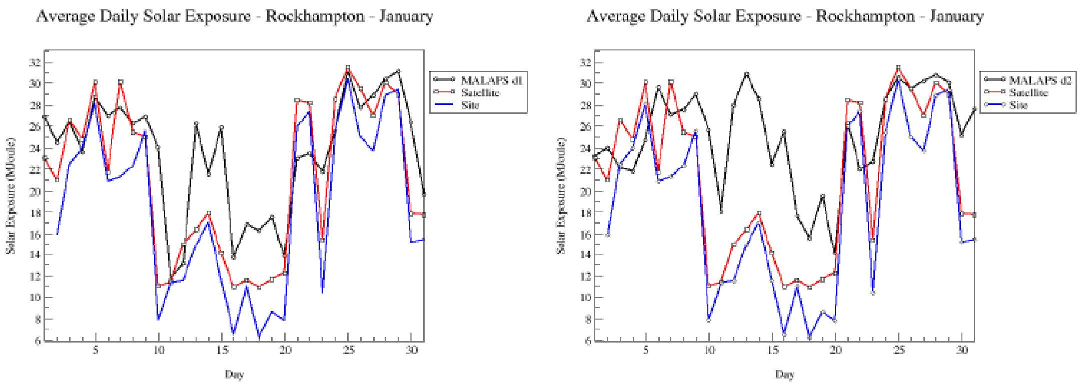

Fig. 22 Comparison between the 1st-day MALAPS forecast (left) and the 2nd-day MALAPS forecast (right) against satellite and site data for Rockhampton in January 2008.

Table 8 *Comparison of accumulated solar exposure between the 1st-and 2nd-day MALAPS forecast against site data for Rockhampton between January 11th-15th.*

Date	1stday forecast	2ndday forecast	Site	Δ1stday	Δ2ndday
11th	11.76	18.11	11.37	0.39	6.74
12th	13.17	27.95	11.50	1.67	16.45
13th	26.60	30.92	14.90	11.70	16.02
14th	21.72	28.62	17.03	4.69	11.59
15th	25.78	22.51	11.54	14.24	10.97

The day-to-day trend of the NWP against the site observations is exact, suggesting that the forecast of the NWP cloud amounts are good (i.e. the NWP has predicted successfully the passing of a cloud band). However, the difference in magnitude between the NWP and site exposure values remains fairly constant.

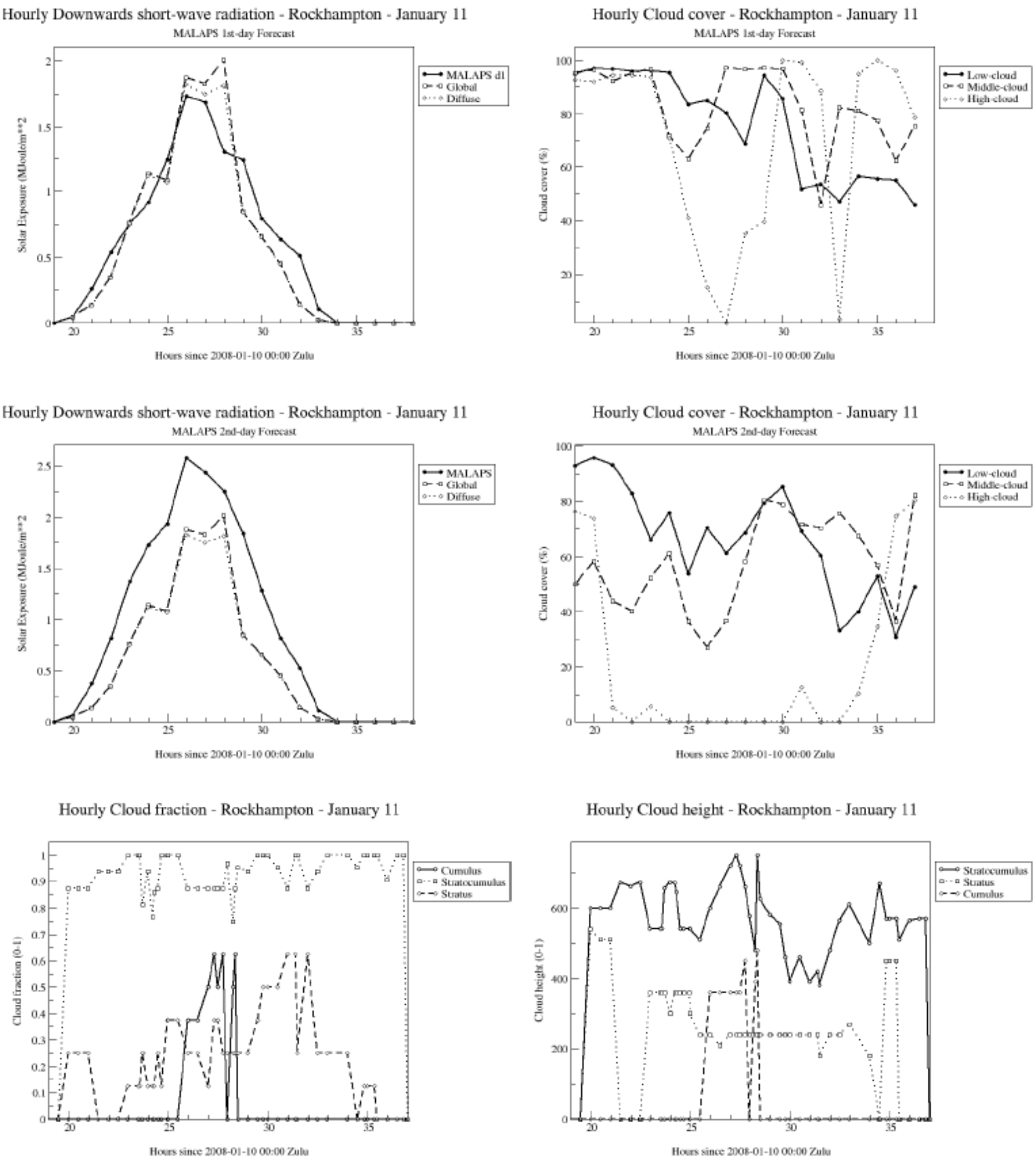

Fig. 23 Analysis of hourly change in computed exposure and cloud cover for 1st-day forecast (top) and 2nd-day forecast (middle) for Rockhampton on January 11. Site-based exposure values are super-imposed on the exposure plot. The observed cloud properties are also shown (bottom).

In addition, the 1st day forecast values show good agreement on some days (11th and 12th) but deteriorate after this day. Comparisons of the 1st and 2nd-day forecast is given in fig. 23. Plots for observed and computed exposure and cloud properties at Rockhampton for January 11 are also shown in this figure. This is an overcast day where the observed solar exposure is almost entirely diffuse. The agreement for the 1st-day forecast is excellent, while the 2nd-day forecast computes higher levels of solar exposure during the day.

Examining the computed cloud features show that the 1st-day forecast predicts very large cover of low and middle cloud, with the 2nd-day forecast predicting 20-30% less cloud. The cloud observations are dominated by stratocumulus and stratus at heights of roughly 500 and 300 metres respectively. Based on the results for this day, the NWP is able to accurately predict the optical thickness of stratocumulus and stratus. The errors observed for the 2nd-day forecast are due to too little cloud being present.

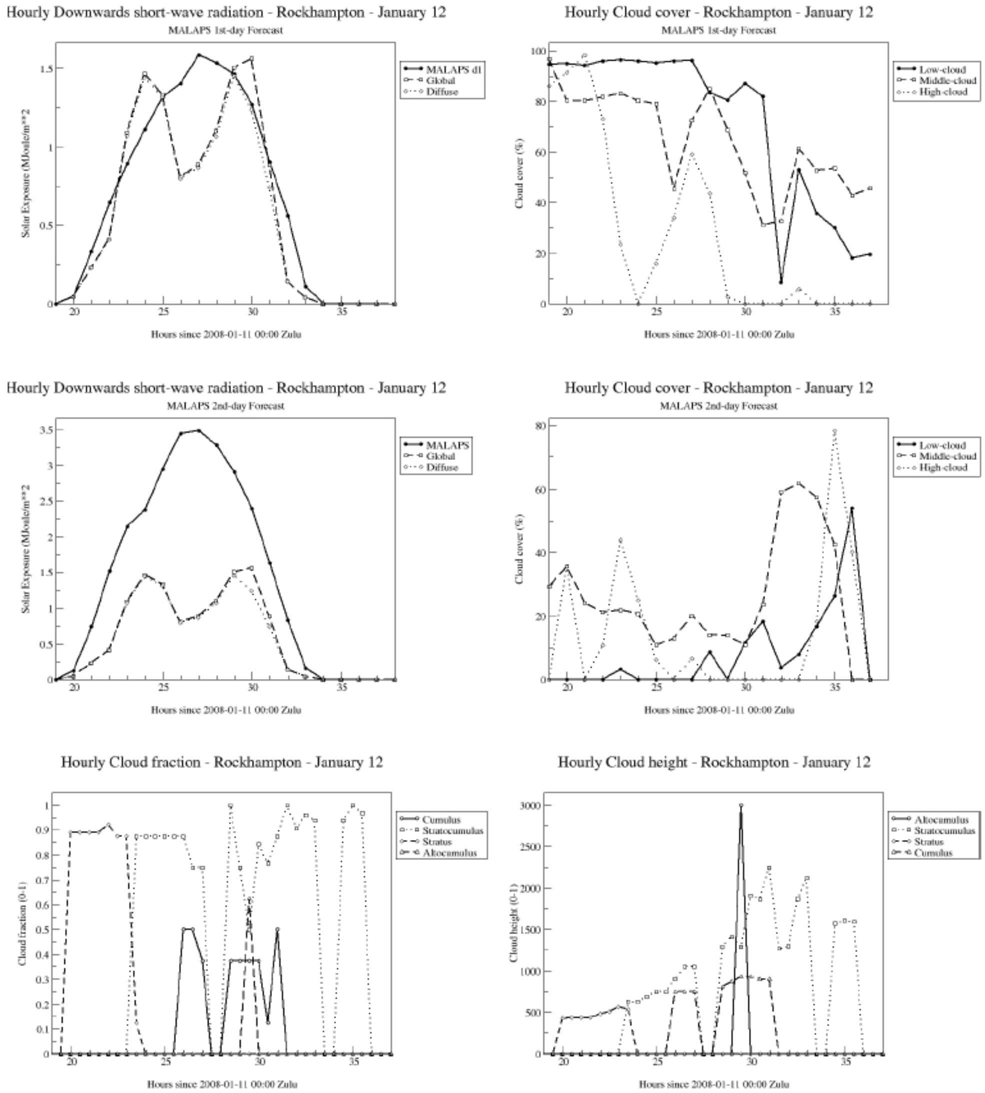

Fig. 24 Analysis of hourly change in computed exposure and cloud cover for 1st-day forecast (top) and 2nd-day forecast (middle) for Rockhampton on January 12. Site-based exposure values are super-imposed on the exposure plot. The observed cloud properties are also shown (bottom).

Analysis of January 12th at Rockhampton is shown in fig. 24. This is another cloudy day dominated by diffuse radiation. The 1st-day forecast shows large amounts of low and middle cloud, although the % of cloud cover begins to decrease in the afternoon in conjunction with increasing high cloud. The 2nd-day forecast predicts patchy cloud-cover. The observed cloud fields are dominated by stratocumulus, with some stratus in the morning, and a period of cumulus around midday. It is at this point of the day where the NWP shows no attenuation relative to the observed exposure. This error can be attributed to a temporal error in the predicted cloud field, in particular due to the large increase in cloud cover around midday which the model appears to represent as high cloud which is systematically too optically thin in this version of the models.

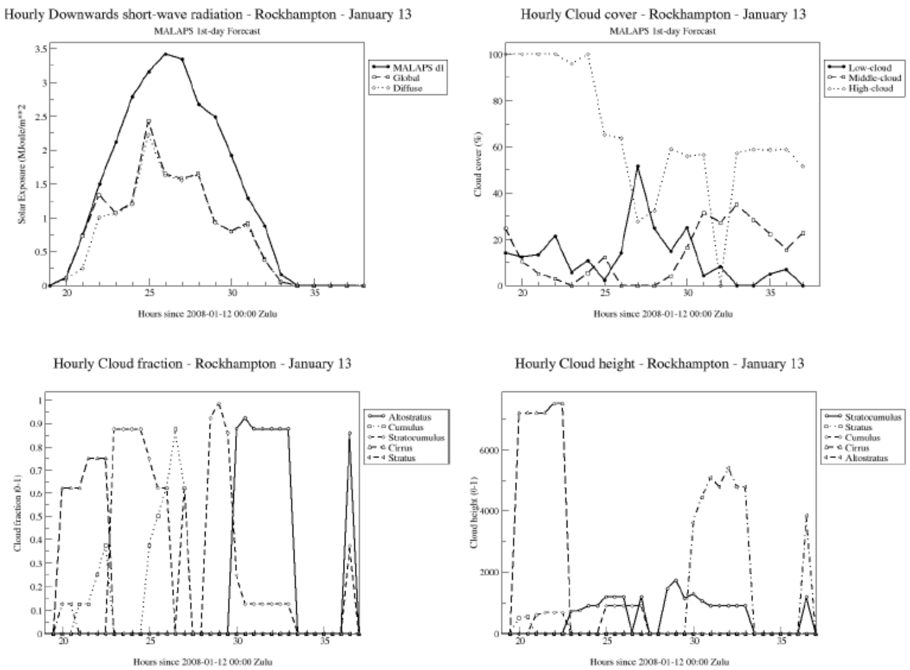

Fig. 25 Analysis of hourly change in computed exposure and cloud cover for 1st-day forecast (top) for Rockhampton on January 13. Site-based exposure values are super-imposed on the exposure plot. The observed cloud properties are also shown.

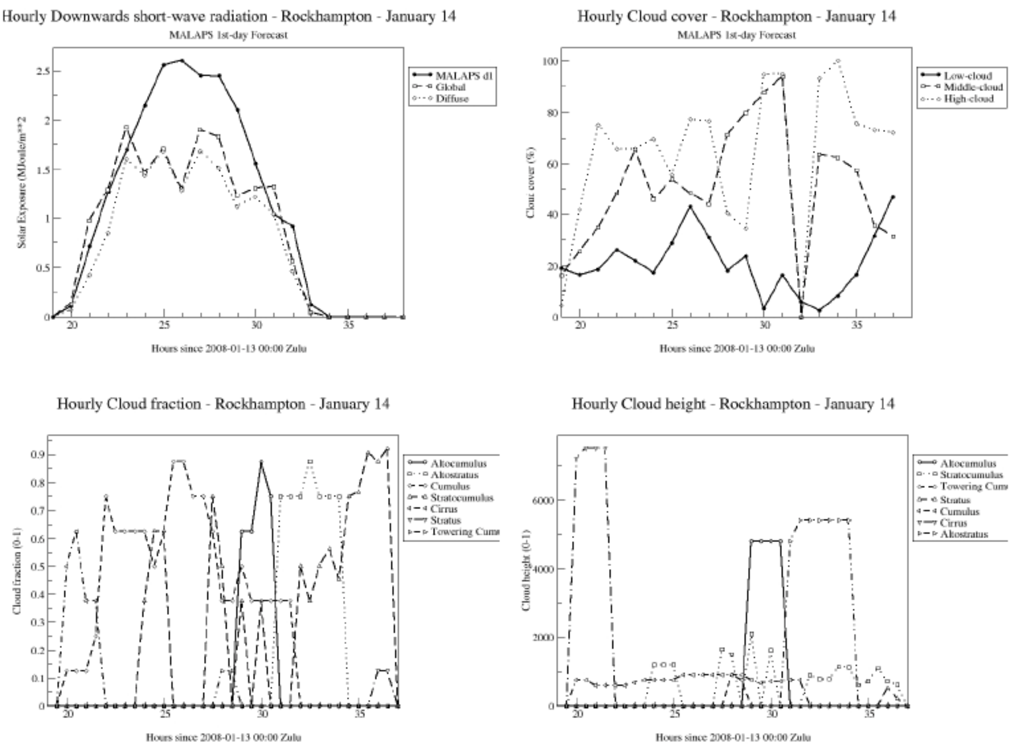

Fig. 26 Analysis of hourly change in computed exposure and cloud cover for 1st-day forecast (top) for Rockhampton on January 14. Site-based exposure values are super-imposed on the exposure plot. The observed cloud properties are also shown (bottom).

The 2nd-day forecast continues to under predict the cloud cover for the remainder of the period of January 11th to 15th, so any errors with solar attenuation due to optical thickness will be impossible to separate from errors created from incorrect cloud amounts. Therefore, the rest of this analysis for this period will concentrate on the 1st-day forecast only, which gave more accurate cloud amounts.

The site-based exposure data for January 13th (fig. 25) shows another overcast day dominated by diffuse exposure. The predicted cloud fields featured large amounts of high cloud with a smaller contribution from low cloud. The observed cloud fractions show large contributions from high cloud types (altostratus and cirrus) with smaller contributions from lower cloud types such as stratocumulus. The day began with some high cirrus, but by midmorning the sky was dominated by low cloud (cumulus and stratocumulus). In the afternoon, the low cloud diminished and middle level cloud (altostratus) dominated the sky.

The plot of hourly predicted and observed solar exposure shows that the forecast exposure over predicts the observed exposure by roughly 80%. This confirms the expected finding that the NWP doesn’t compute optical thickness for high-cloud types as well as it does for low-cloud types.

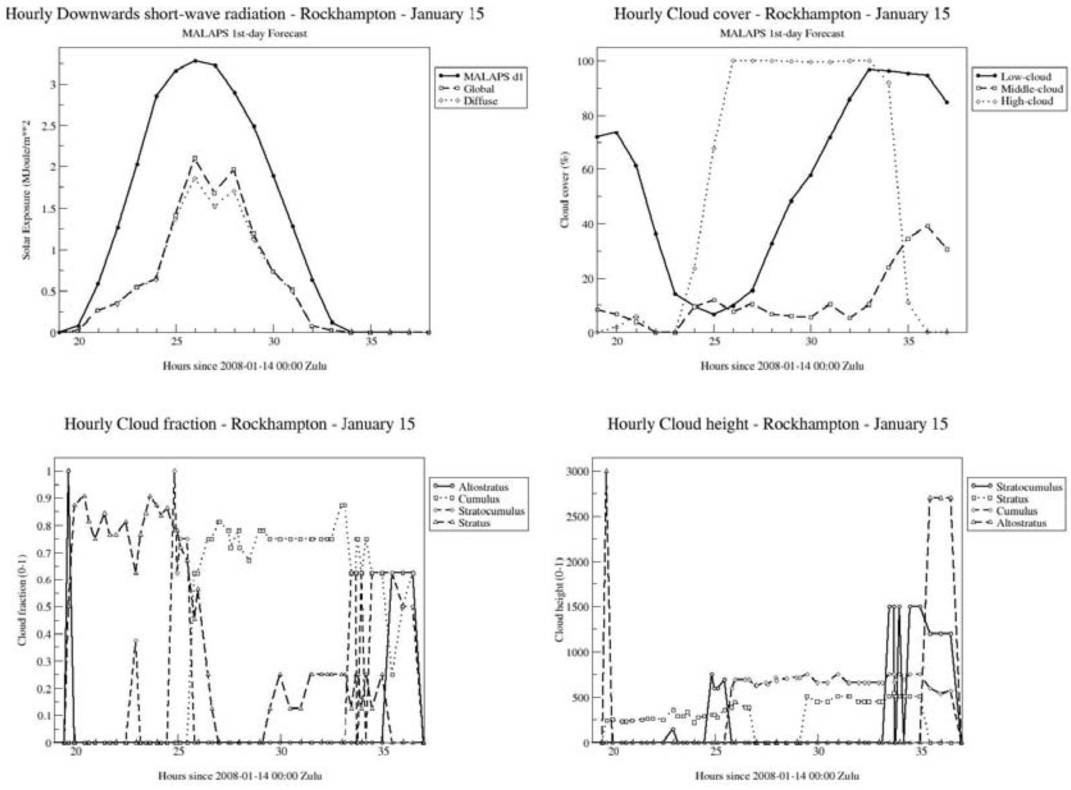

Fig. 27 Analysis of hourly change in computed exposure and cloud cover for 1st-day forecast (top) for Rockhampton on January 15. Site-based exposure values are super-imposed on the exposure plot. The observed cloud properties are also shown (bottom).

Analysis of cloud formation and exposure for the following day (January 14th) shows a similar pattern to the 13th. Figure 26 shows the temporal development of the observed cloud over the day is the same, with low cloud predominant in the morning, with higher level cloud dominating in the afternoon. The NWP cloud fields are slightly different, with fairly constant values of cloud type during the day. However, the middle and high clouds are always dominant. Hence, the predicted exposure is higher than the measured values.

The predicted cloud fields for the 15th of January are not accurate enough to enable any meaningful comparisons. Figure 27 shows the NWP predicts a solid cover of high cloud through most of the day, whereas the observations show the cloud cover was predominantly low cloud (cumulus and stratus) with high cloud (altostratus) only appearing towards the day's end.

This analysis highlights the difficulties in assessing the NWP model's ability to compute the correct solar attenuation through clouds, as the forecast has to predict cloud fields that are close enough to the observed fields to remove this component as a possible source of error in the exposure calculation.

5.3.2 Melbourne - January 11th -15th

This analysis is repeated for the same time period at Melbourne Airport. Figure 28 shows the results for the 1st and 2nd-day MALAPS forecast compared with the satellite and site-based data. The satellite and site based data suggests that Melbourne experienced significant cloud cover on the 11th and 13th of January, but the other days were relatively clear. This figure also shows that the NWP forecasts perform better than the satellite data on some days.

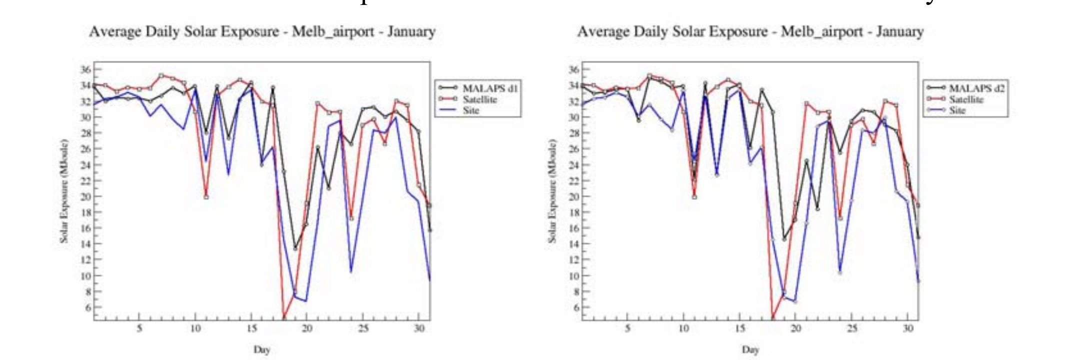

Fig. 28 Comparison between the 1st-day MALAPS forecast (left) and the 2nd-day MALAPS forecast (right) against satellite and site data for Melbourne in January 2008.

The values of the daily accumulated solar exposure for these days are given in table 9. The results show that in this instance, the 2nd-day forecast produced more accurate results for the cloudy days; however the 1st-day forecast gave slightly better agreement for the clearer-skies days.

Table 9 *Comparison of accumulated solar exposure between the 1st-and 2nd-day MALAPS forecast against site data for Melbourne Airport between January 11th-15th.*

Date	1stday forecast	2ndday forecast	Site	Δ1stday	Δ2ndday
11th	28.70	22.07	24.33	4.37	-2.26
12th	33.86	34.22	32.80	1.06	1.42
13th	27.07	22.46	22.67	4.40	-0.21
14th	32.26	33.25	31.56	0.70	1.69
15th	34.31	34.04	33.32	0.99	0.72

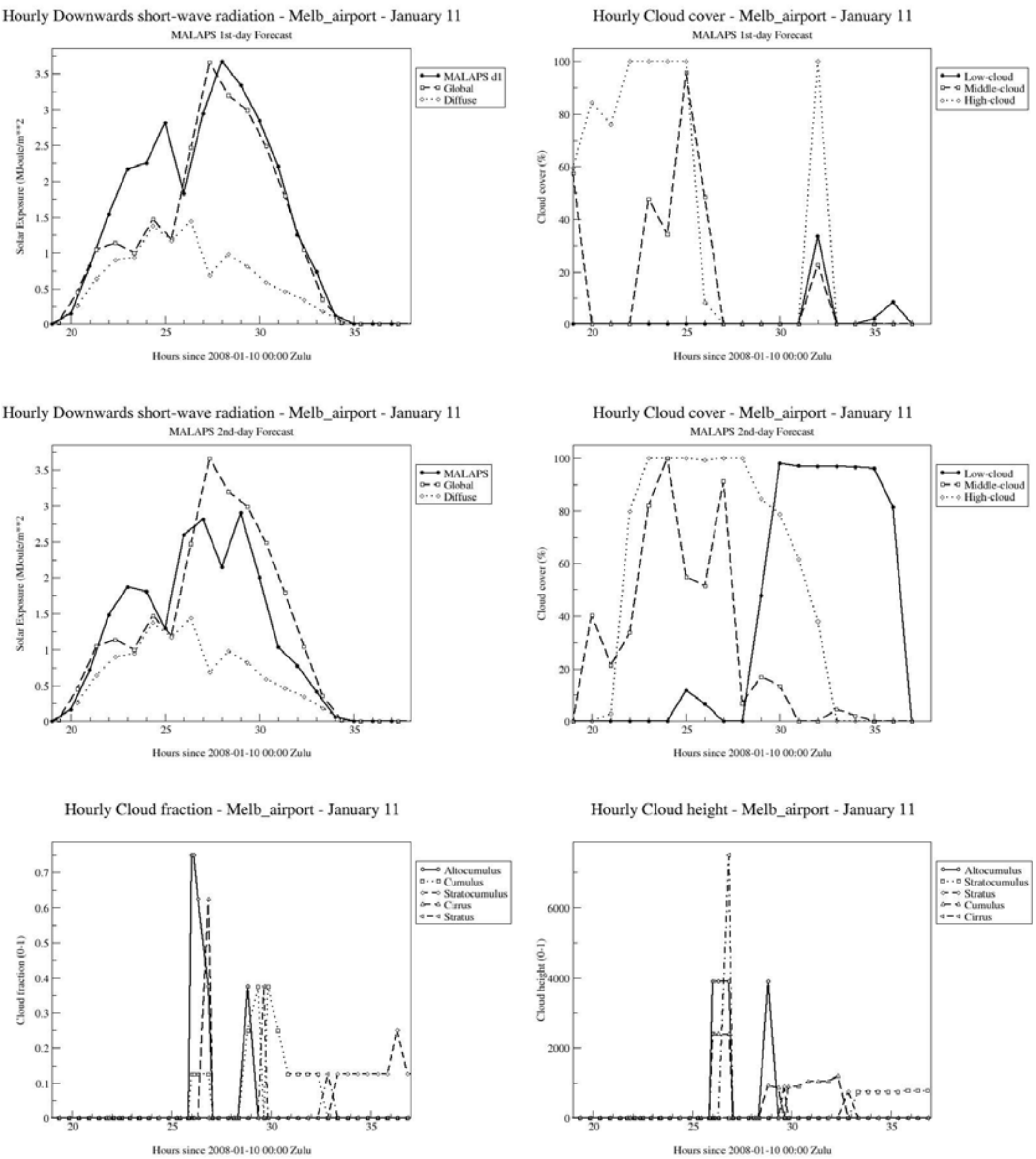

Fig. 29 Analysis of hourly change in computed exposure and cloud cover for 1st-day forecast (top) and 2nd-day forecast (middle) for Melbourne on January 11. Site-based exposure values are superimposed on the exposure plot. The observed cloud properties are also shown (bottom).

The results for January 11th at Melbourne airport (fig. 29) show that neither forecast produces realistic cloud fields. The observational data shows that there was some high and middle-level cloud around midday, with some low cloud (cumulus and stratus) in the afternoon.

The 1st-day forecast predicts too much cloud in the morning (and almost clear skies in the afternoon), while the 2nd-day forecast predicts too much cloud, with almost 100% cloud cover present during most of the day.

The agreement for January 12th is much better (not shown). Both forecasts predict almost entirely clear-sky days. The observed cloud pattern showed patches of stratocumulus in the morning, but with clear skies in the afternoon.

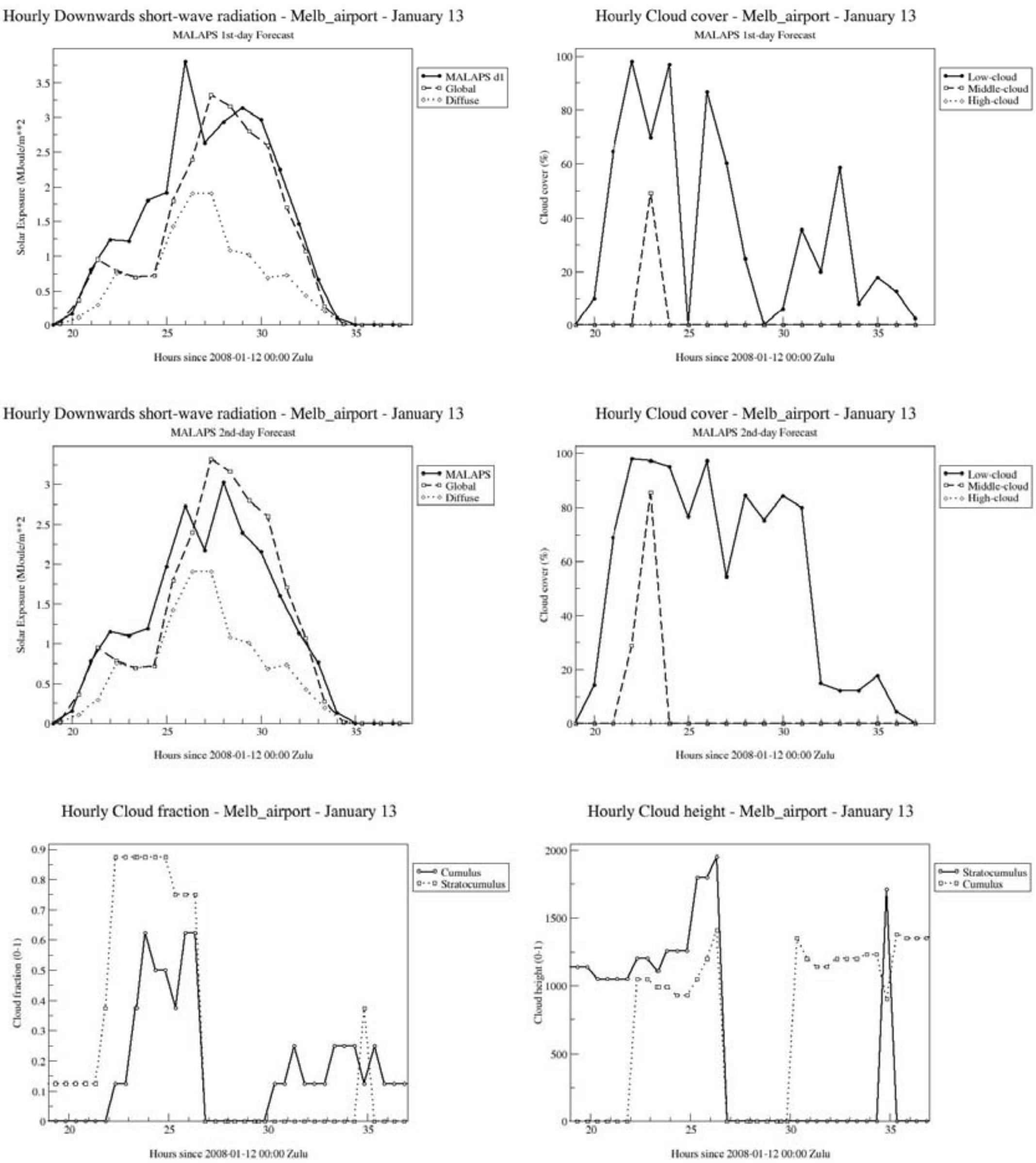

Fig. 30 Analysis of hourly change in computed exposure and cloud cover for 1st-day forecast (top) and 2nd-day forecast (middle) for Melbourne on January 13. Site-based exposure values are super-imposed on the exposure plot. The observed cloud properties are also shown (bottom).

January 13th saw the return of cloudy skies at Melbourne airport. Figure 30 shows the 2nd-day forecast predicted heavier cloud cover, with 80-100% low cloud cover for most of the day. The 1st-day forecast predicted less cloud cover. The observed cloud data show large cloud fractions of low cloud (cumulus and stratocumulus) in the morning, with a break around midday, and patchy low cloud in the afternoon.

The 1st-day forecast doesn't provide enough low cloud cover to sufficiently attenuate the incoming solar exposure, therefore it over predicts the accumulated exposure during the day. The 2nd-day forecast has enough cloud so that it produces an accurate value of the daily solar exposure. This is another example showing that the model is able to predict accurately solar exposure through low cloud types (cumulus and stratocumulus).

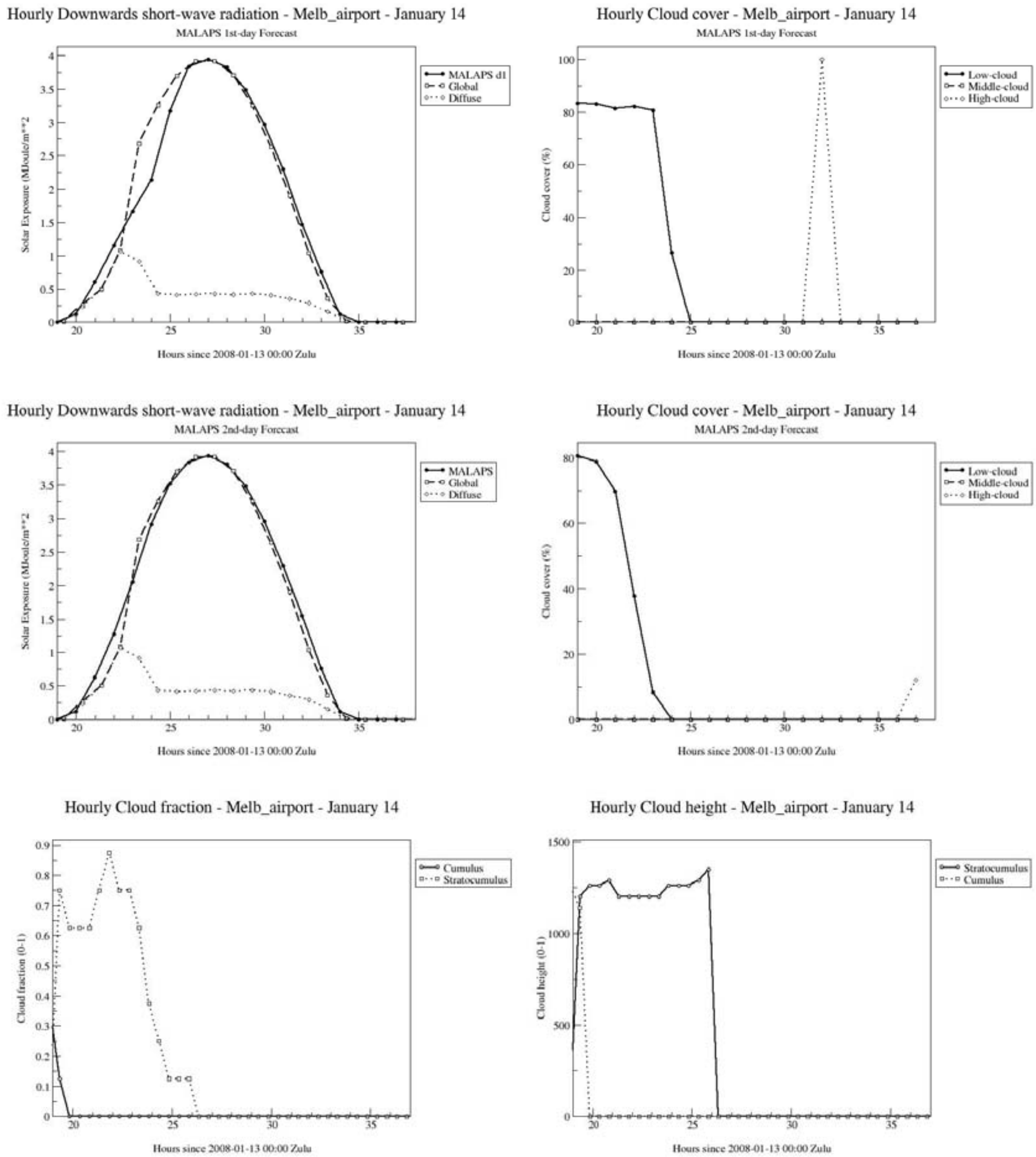

Fig. 31 Analysis of hourly change in computed exposure and cloud cover for 1st-day forecast (top) and 2nd-day forecast (middle) for Melbourne on January 14. Site-based exposure values are superimposed on the exposure plot. The observed cloud properties are also shown (bottom).

January 14th and 15th both show a return to mainly clear-sky conditions. The results for January 14th (given in fig. 31) show that both forecasts predict large amounts of low cloud occurring in the early morning, and clear skies in the afternoon. This is in excellent agreement with the observed cloud fields, which has large coverage of stratocumulus in the early morning. It is no surprise then that the computed exposure for this day shows excellent agreement with the observed data, further evidence that the model's estimate of optical thickness for low cloud is reasonable.

Both forecasts predicted zero cloud cover for the 15th of January, which is exact agreement with the observed cloud (not shown). Naturally, the clear-sky exposures computed for this day are in excellent agreement with the observed measurements.

5.3.3 Melbourne - May 6th -10th

As noted previously in § 5.1, it was found that at various times in May the NWP systems provided superior estimates of observed exposure values than the corresponding satellite measurements. This trend was most significant in Alice Springs and in Melbourne. Some results from Melbourne are analysed below.

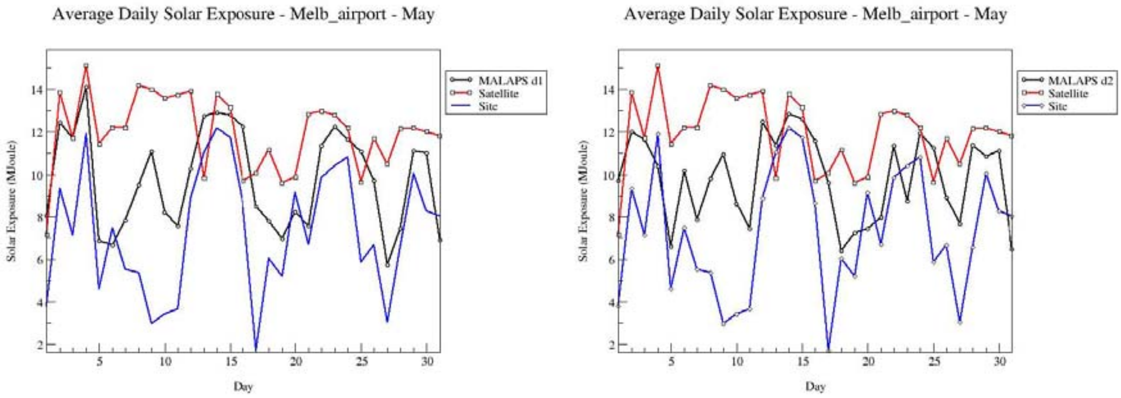

Fig. 32 Comparison between the 1st-day MALAPS forecast (left) and the 2nd-day MALAPS forecast (right) against satellite and site data for Melbourne in May 2008.

Table 10 *Comparison of accumulated solar exposure between the 1st-and 2nd-day MALAPS forecast against site data for Melbourne Airport between May 6th-10th.*

Date	1st-day forecast	2nd-day forecast	Site	Δd1	Δd2
6th	7.47	10.24	6.64	0.83	3.6
7th	7.82	7.68	5.51	2.31	2.17
8th	9.30	9.72	5.36	3.94	4.36
9th	10.90	11.02	2.95	7.95	8.07
10th	8.27	8.75	3.41	4.86	5.34

Figure 32 shows that the satellite continually over predicts the daily solar exposure at Melbourne Airport. The NWP forecasts do a better job, although they still show some significant errors, particular on very cloudy days with a large amount of solar attenuation.

Table 10 shows the exposure values for the NWP data and site observations between May 6th-10th. Except for the 1st-day forecast for the 6th of May, the NWP results fail to predict the observed exposure values. However, they are still superior to the satellite data.

Figure 33 shows the predicted cloud fields and computed exposure for May 6th (along with the observed data). The 1st-day forecast cloud field predicts almost complete cloud cover over most of the day, comprising mostly of low and middle level cloud. The 2nd-day forecast predicts less cloud coverage, in particular low cloud. The observed cloud fractions show large amounts of low cloud (cumulus and stratocumulus) with some higher middle level cloud (altocumulus).

The exposure plots show that the day was partly cloudy in the morning (with diffuse exposure comprising just over half of the total measured exposure), but overcast in the afternoon (diffuse exposure comprising all of the measured exposure). The 1st-day forecast provides a good estimate of the accumulated exposure over the day, even though the hourly values during the day are different to the observations. Evidently, the forecast of the overall cloud field is good enough to predict accurate solar attenuation over the day, indicating that the site behaves very much like the entire area represented by the model grid resolution but with a slightly different temporal behaviour.

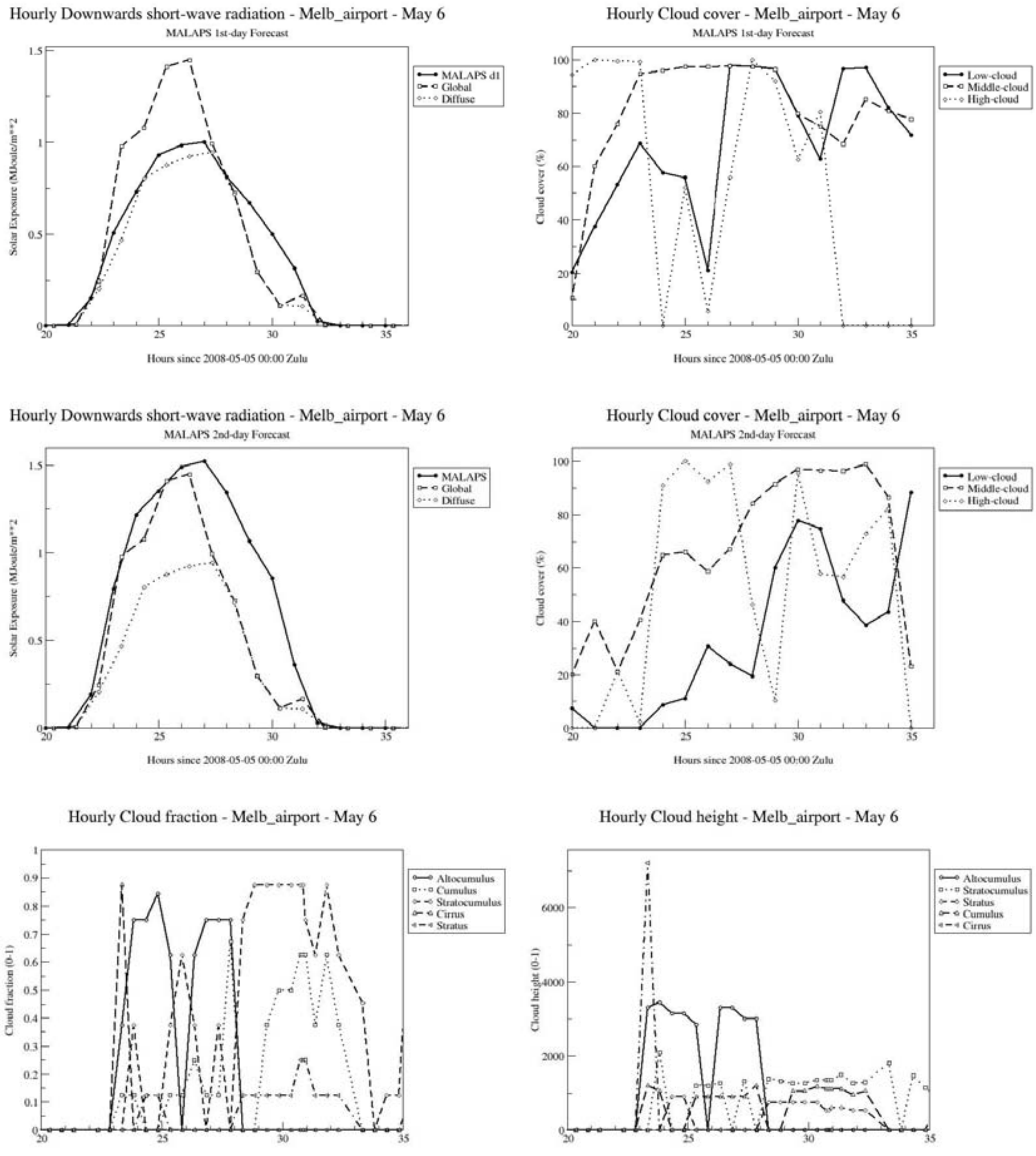

Fig. 33 Analysis of hourly change in computed exposure and cloud cover for 1st-day forecast (top) and 2nd-day forecast (middle) for Melbourne on May 6. Site-based exposure values are superimposed on the exposure plot. The observed cloud properties are also shown (bottom).

In contrast, the sparser cloud field predicted by the 2nd-day forecast fails to produce enough attenuation. These results continue to support the view that the NWP can accurately simulate solar attenuation through stratocumulus and cumulus cloud. The results for May 7th are shown in fig. 34. This was another overcast day. The 1st-day forecast cloud fields featured almost 100% low cloud cover, with some afternoon middle cloud cover. The 2nd-day forecast featured less low cloud cover, with more middle and high cloud.

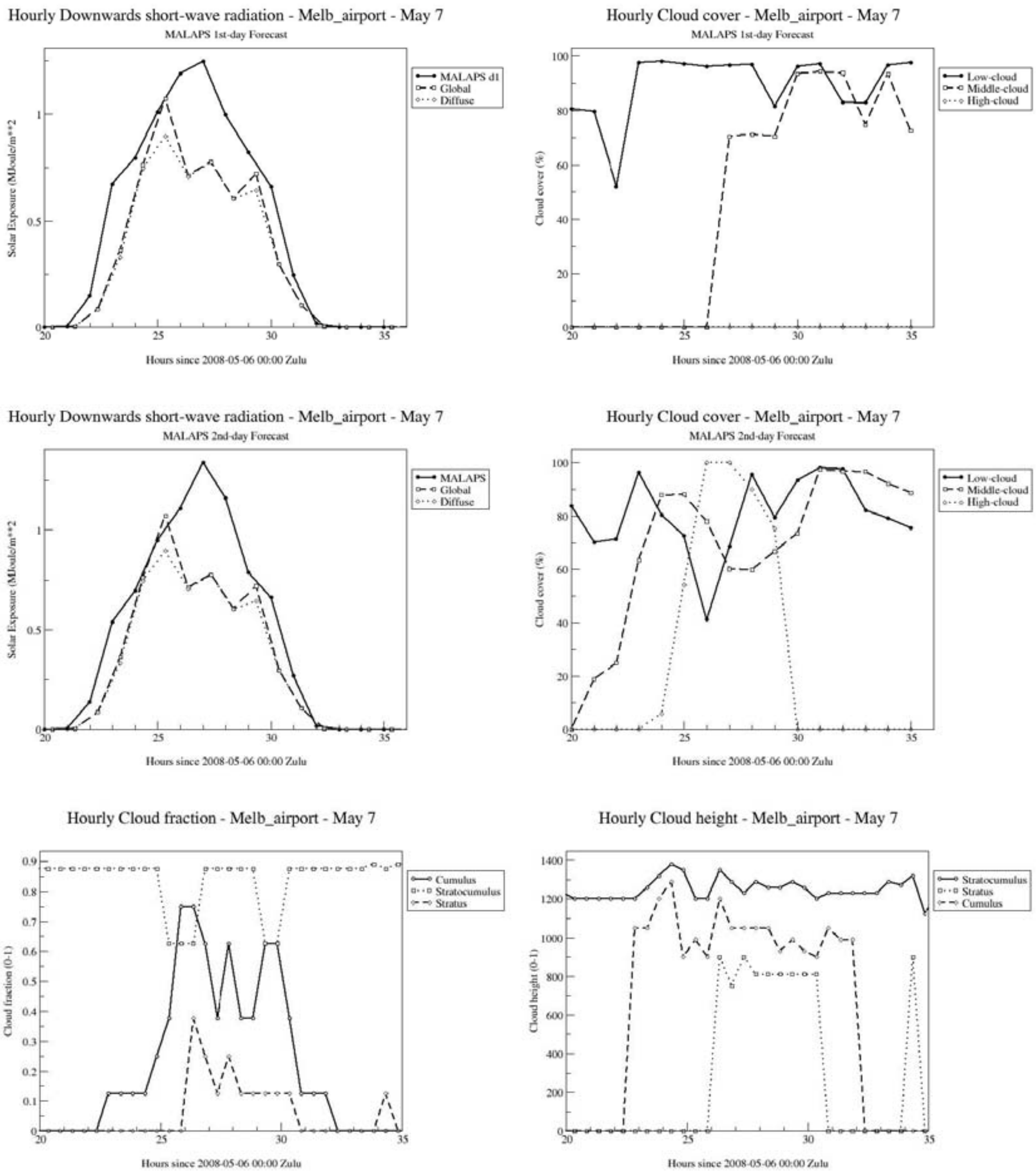

Fig. 34 Analysis of hourly change in computed exposure and cloud cover for 1st-day forecast (top) and 2nd-day forecast (middle) for Melbourne on May 7. Site-based exposure values are super-imposed on the exposure plot. The observed cloud properties are also shown (bottom).

As with the previous day, the 1st-day forecast cloud field is more accurate, as the observed cloud shows almost complete coverage of stratocumulus during the day, with small patches of stratus.

May 8th was another overcast day. For brevity's sake, only the 1st-day forecast will be shown, as the 2nd-day forecast continues the trend from the May 6th and 7th, i.e. slightly less cloud cover. As with the previous days, it was an almost completely overcast day. The predicted cloud field featured 80-100% coverage for low cloud.

The observed cloud fields (shown in fig. 35 show almost complete cloud coverage with stratocumulus. Although there is reasonable agreement between the two cloud fields, the NWP value for exposure is almost double the observed value. This large error may be attributable to the lower forecast cloud cover versus the observed cloud cover (80% cloud cover versus 0.875 cloud fraction) but probably involves an optical depth error as well.

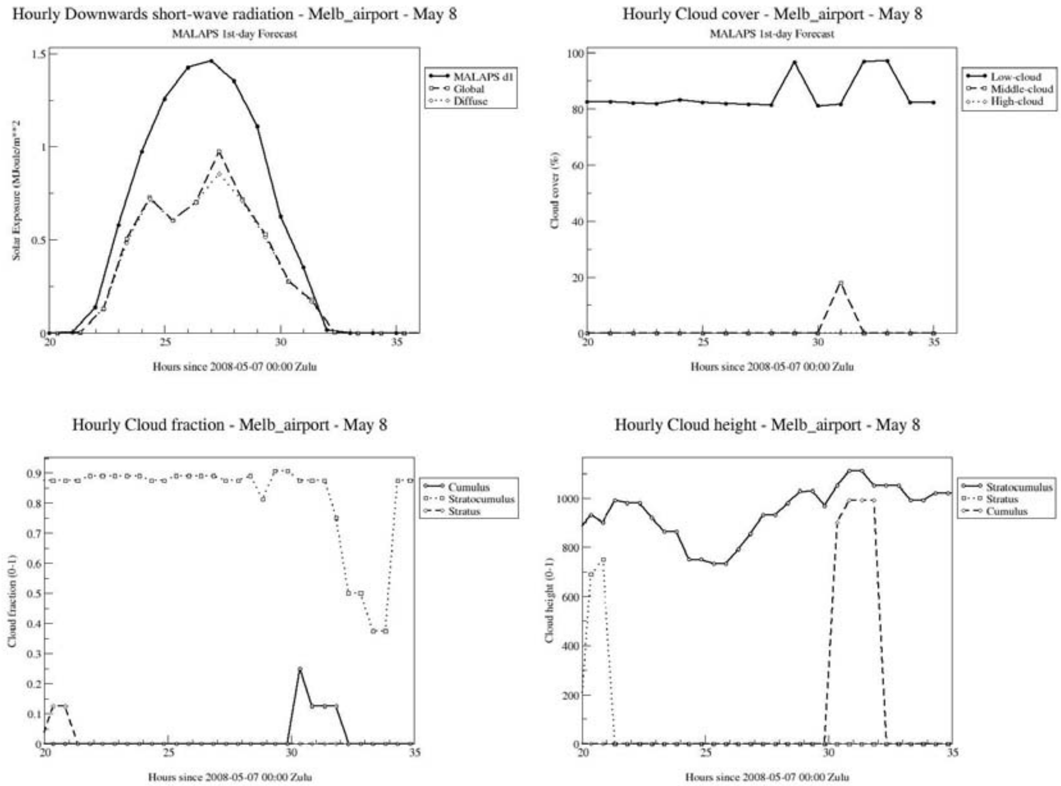

Fig. 35 Analysis of hourly change in computed exposure and cloud cover for 1st-day forecast (top) for Melbourne on May 8. Site-based exposure values are super-imposed on the exposure plot. The observed cloud properties are also shown (bottom).

The results for May 9th are shown in fig. 36. For this day, the predicted cloud cover is again less than the observed cloud fraction, in particular during the morning. This results in a large discrepancy in predicted solar exposure (i.e. the NWP data is three times greater than the observed exposure).One interesting feature is that for May 9th, the predominant cloud type was stratus, as opposed to the cumulus or stratocumulus analysed previously. Further analysis would be required to determine whether or not the change in cloud type has contributed to the error, or discrepancies in overall cloud coverage are responsible.

Analysis for May 10th show identical features to May 8th. Predicted low cloud is roughly 80% low cloud coverage, versus a 0.9 (and higher) cloud fraction of stratocumulus, with additional cumulus and stratus clouds. As before, the NWP predicts an exposure value over double the observed value.

The results suggest that during the Autumn months, small discrepancies in the computed cloud coverage can greatly affect the accuracy of the computed exposure, mainly because of the smaller amounts of exposure that are reaching the site at this time of year. Additionally, the greater solar zenith angles make the radiation more sensitive to attenuation by partial cloud cover. Therefore, cloud attenuation causes a larger change in exposure. It is difficult, however, to discount the role of cloud optical thickness in the error without more information.

Of additional interest is the inability of the satellite to accurately simulate the downwards exposure reaching the surface.

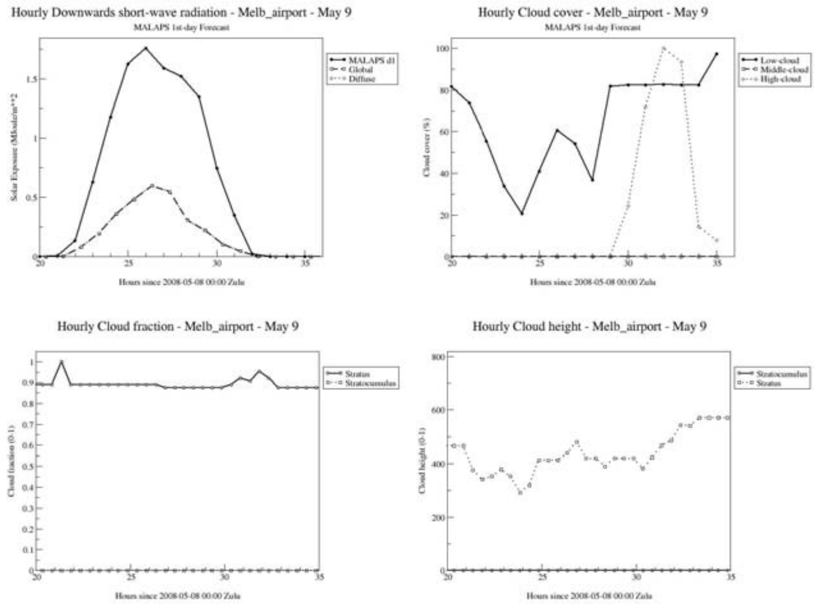

Fig. 36 Analysis of hourly change in computed exposure and cloud cover for 1st-day forecast (top) for Melbourne on May 9. Site-based exposure values are super-imposed on the exposure plot. The observed cloud properties are also shown (bottom).

5.3.4 Alice Springs - May 7th -10th

The final hourly analysis was carried out at Alice Springs. These results show the ability of the NWP codes to predict more accurately clear-sky days than the satellite data and indicate that the bias correction in the satellite algorithm may need to be adjusted.

Table 11 *Comparison of accumulated solar exposure between the 1st-and 2nd-day MALAPS forecast against site data for Alice Springs between May 7th-10th.*

Date	1st-day forecast	2nd-day forecast	Site	Δd1	Δd2
7th	19.97	19.88	19.12	0.85	0.76
8th	19.41	19.00	14.84	4.57	4.16
9th	19.84	19.91	19.24	0.59	0.66
10th	19.66	19.78	19.05	0.61	0.73

Figure 37 and table 11 shows that both forecasts produce bad results for May 8th, but the overall agreement during the other clear-sky days is excellent. Hourly plots for the days noted in table 11 are shown in figs 38 - 41.

Results for May 7th are shown in fig. 38. There were no observed cloud features for this day, while both forecasts predict some high cloud cover during the day. Evidently, the computed high clouds produce small levels of solar attenuation so that there is little-to-no difference in the computed solar exposure at Alice Springs on this day.

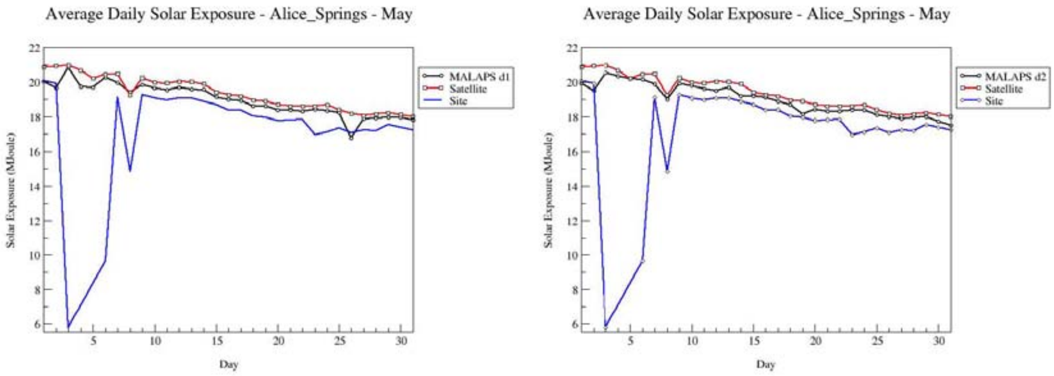

Fig. 37 Comparison between the 1st-day MALAPS forecast (left) and the 2nd-day MALAPS forecast (right) against satellite and site data for Alice Springs in May 2008. Note the incomplete site data between the 3rd and 6th of May.

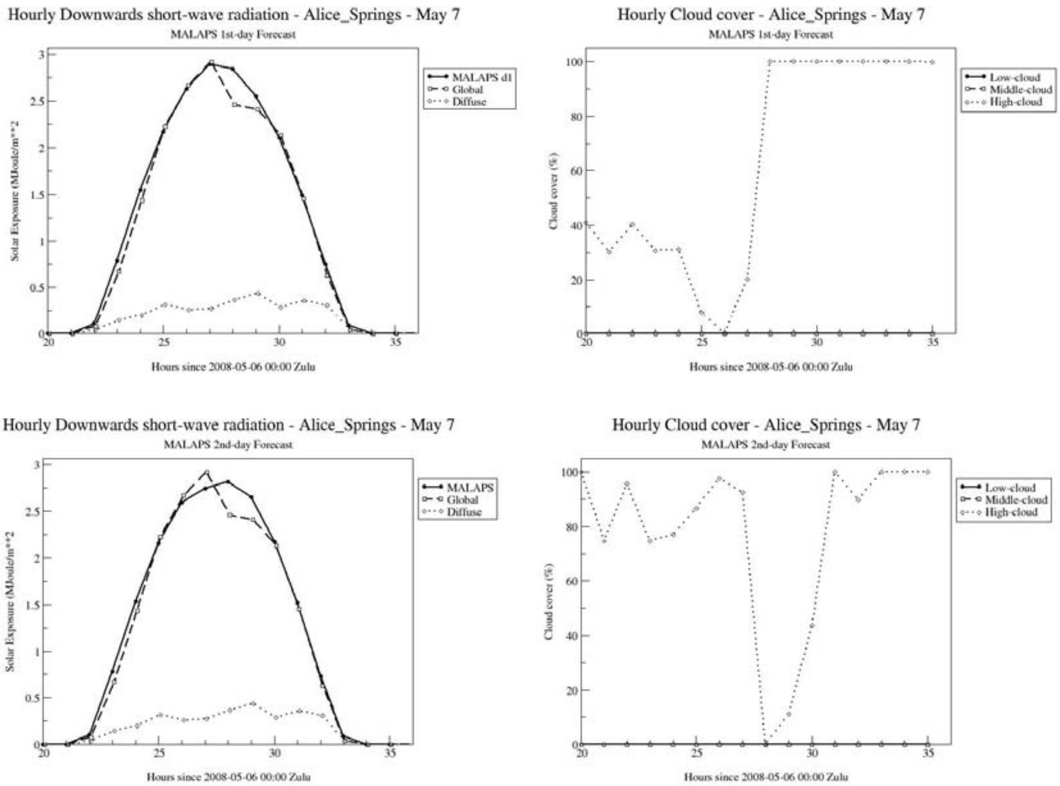

Fig. 38 Analysis of hourly change in computed exposure and cloud cover for 1st-day forecast (top) and 2nd-day forecast (bottom) for Alice Springs on May 7. Site-based exposure values are super-imposed on the exposure plot. There were no observed cloud features.

The observed exposure data for May 8th (fig. 39) shows that the day featured a large amount (roughly 50%) of diffuse exposure, suggesting the day featured some cloud cover. However, the observed cloud data recorded no cloud features. The forecast data once again shows almost 100% high-cloud cover.

The discrepancies for this particular day are difficult to explain as it would appear that the cloud observation data is incorrect, judging by the amount of diffuse exposure measured during the day The forecast data for May 9th (fig. 40) shows almost clear-sky conditions, with both the 1st and 2nd-day forecasts predicting only tiny amounts of cloud coverage. Therefore, the computed exposure is almost exactly equal to the observed exposure for this day.

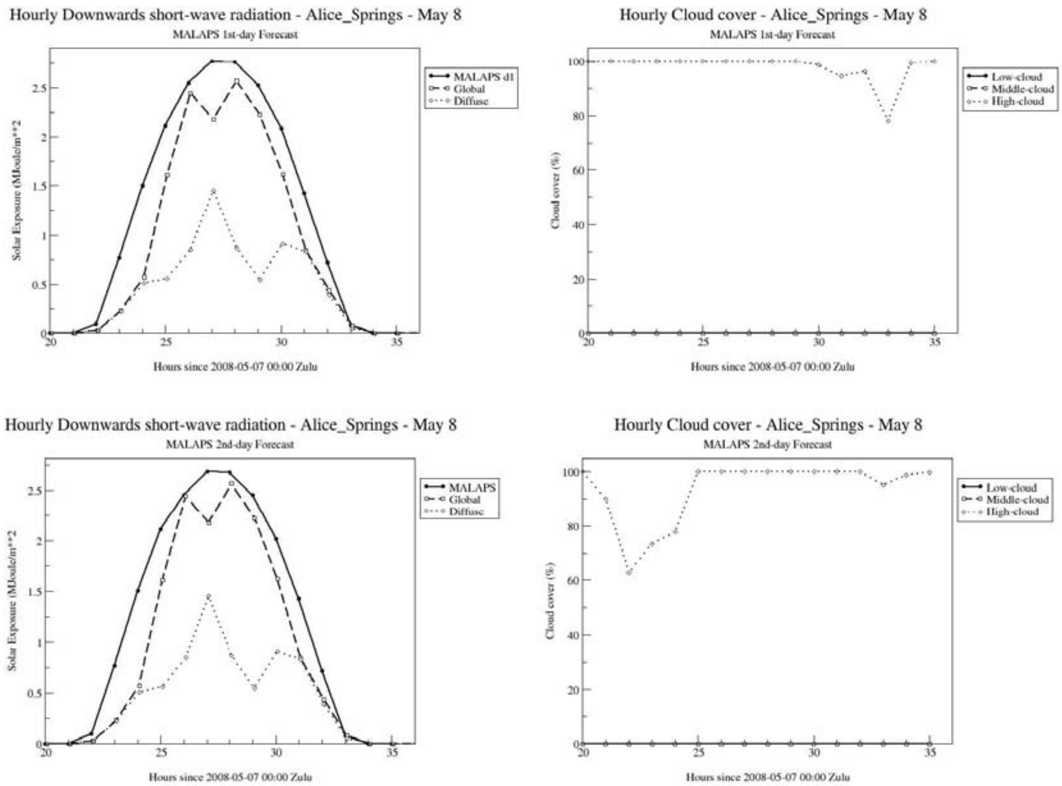

Fig. 39 Analysis of hourly change in computed exposure and cloud cover for 1st-day forecast (top) and 2nd-day forecast (bottom) for Alice Springs on May 8. Site-based exposure values are superimposed on the exposure plot. There were no observed cloud features.

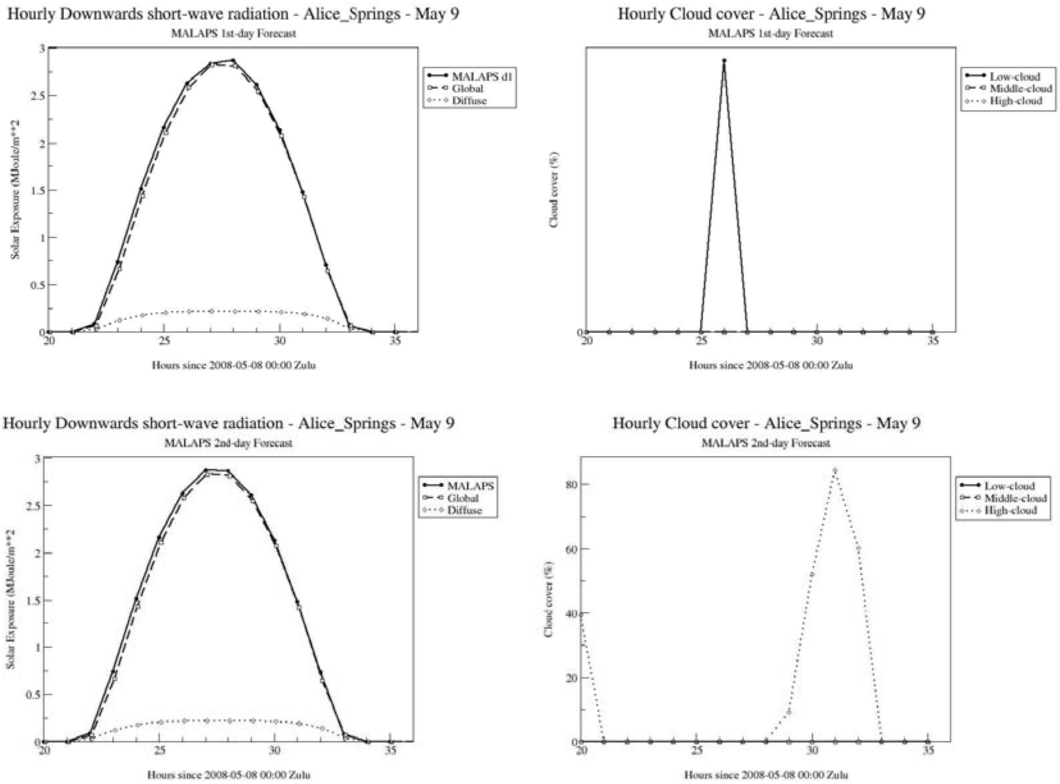

Fig. 40 Analysis of hourly change in computed exposure and cloud cover for 1st-day forecast (top) and 2nd-day forecast (bottom) for Alice Springs on May 9. Site-based exposure values are superimposed on the exposure plot. There were no observed cloud features.

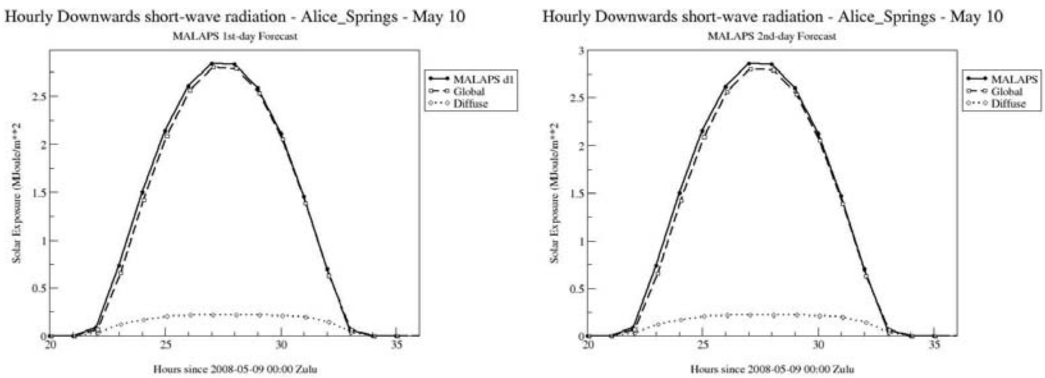

Fig. 41 Analysis of hourly change in computed exposure and cloud cover for 1st-day forecast (left) and 2nd-day forecast (right for Alice Springs on May 10. Site-based exposure values are superimposed on the exposure plot. There were no forecast or observed cloud features.

Figure 41 shows the results for May 10th. This was a completely clear-sky day, in which no clouds were observed or predicted. As expected, the NWP provides an almost exact prediction of the solar exposure. Any errors for this day are probably related to numerical errors such as downscaling errors, discretisation errors in the numerical methods, etc.

5.4 Section summary

Average monthly results at the eight surface exposure measurement sites confirmed the analysis from section 4, namely the NWP model cannot produce accurate solar exposure forecasts in the summer months in the tropics. However, outside of summer, the NWP forecasts were more accurate than the satellite data at these latitudes. At the mid-latitude sites, the NWP model performs slightly worse than the satellite data at Alice Springs and Wagga Wagga, and arguably slightly better at Adelaide. The NWP forecasts for the two most southerly stations (Melbourne and Cape Grim) are poor, and are on par with the two tropical stations (Darwin and Rockhampton) during summer.

Daily analysis showed that the NWP tropical forecasts in summer failed to accurately predict exposure on very cloudy days (i.e. days with low solar exposure) Although the qualitative behaviour of the forecasts was correct, there was an almost constant offset between the NWP forecasts and the site measurements. The satellite data showed poor performance at Melbourne in the summer, with the NWP forecast producing better agreement with the day-to-day variance of exposure as measured at the site. In the winter months, the mid-latitude sites of Adelaide, Alice Springs and Wagga Wagga show that the NWP data gives better estimates of solar exposure than the satellite.

Comparison of hourly NWP forecast exposure and cloud coverage at Rockhampton showed that the NWP model accurately predicted the solar attenuation through low cloud types (e.g. cumulus and stratocumulus), but it computed too little solar attenuation through high cloud types (e.g. altostratus and cirrus). In other words, the high clouds are almost optically transparent to incoming solar irradiance. Analysis of site data at Melbourne and Alice Springs confirmed these findings. The trend in the NWP solar forecasts to over predict solar surface exposure can be attributed to computation of high cloud fields that are too optically thin.

6 DISCUSSION - NWP VS SITE-BASED OBSERVATIONS

The main benefit of using the site-based observations for exposure and clouds is that it gives a detailed assessment of the NWP code's ability to forecast cloud and to predict solar attenuation through various cloud types. Accurate computation of both factors is required to forecast solar exposure.

As mentioned previously, these two factors are independent of each other. The NWP might be able to compute the correct cloud cover for the day, but it may fail to predict the correct solar attenuation for that cloud type. Conversely, the model may be able to predict solar attenuation for the cloud, but incorrect predictions of cloud cover will produce errors in the forecast solar exposure.

Nevertheless, the analysis presented in the previous section shows that the NWP is able to provide accurate solar exposure forecasts for low-cloud types (specifically cumulus and stratocumulus), provided the predicted cloud-cover is accurate.

These cloud types are convective and in the tropics they develop over the course of the day as moist air warms and rises. It was presumed that this may be the main cause of errors in the tropics in the summer, as this convective process may not be accurately modeled by the NWP code. The analysis from Rockhampton during January suggests that the code can predict reasonable estimates of low-cloud cover during the day. The errors in predicted exposure seem to be greater when the higher level cloud is present (specifically altostratus and altocumulus for the specific days analysed). These clouds are possibly remnants from convective rain events which occurred earlier in the day.

These higher clouds are formed by ice crystals, not water vapour/droplets and therefore they have very different radiation scattering and absorption properties. Ice crystals in clouds can form in a variety of different crystal forms, which makes modeling of ice optical properties very difficult. On days with high level cloud cover, the NWP does not produce enough solar attenuation.

This flaw in the computation of high cloud optical properties was also apparent for observed clear-sky conditions at Alice Springs. At this site, forecasts featuring large amounts of high-cloud cover produced values of exposure that were equal to the observed clear-sky exposure. Subsequent clear-sky forecasts produced almost the same amount of exposure as those days with almost 100% forecast high-cloud cover. Alternatively there may have been sub-visual high level cloud cover which was not observed.

This problem with high-cloud cover is almost certainly due to the parameterization of cloud condensate amount for very cold cloud. High (and higher level middle) level cloud is at relatively low temperature. The parameterization of cloud condensate is a diagnostic based on the cloud temperature and is designed to be too small at low temperature because of the presence of sub-visual cirrus cloud in the model. As the cloud scheme is diagnostic (i.e. has no 'memory' from previous timesteps) the model is unable to determine whether the cirrus is thick anvil produced by recent local convection or sub-visual cloud which has spread out (and thinned out) over the grid over a longer time. To avoid complications due to overemphasising this sub-visual cirrus the model is designed to essentially ignore the radiative effects of all cirrus. This does not discount the possibility that the model's parameterization for ice crystal cloud may also have problems.

7 ACCESS

The NWP codes that were analysed in this report are in the process of being phased out. The ACCESS code, based on a Unified model from the UK Meteorology Office will be used operationally within a year or so. Therefore, there is no opportunity to modify the MALAPS/LAPS codes and repeat sections of this analysis, as these codes will soon be obsolete.

This section presents some preliminary results for the ACCESS model. Some development ACCESS runs have been performed in pseudo-operational mode for the latter half of 2008. There are no complete months archived in 2008, however some day-to-day results were available.

At the time this report was released, the only significant overlap between the ACCESS runs and the available site data was for October 2008. Therefore, the evaluation of results for the ACCESS model is limited to this month.

The ACCESS runs presented here are run on a slightly coarser grid to the MALAPS grid. The ACCESS-A model used a 0.11◦ grid (11.0 km) while the MALAPS model has a resolution of 0.1◦ (10.0 km). It is expected that this slight change in grid resolution will have a minimum effect on the overall results and will still allow meaningful comparisons to be made.

No monthly-averaged analysis was carried out for the ACCESS data as several days of forecast data were missing. The archived October ACCESS data is missing for October 3rd, October 8th and October 28th-30th inclusive. This creates missing data for October 4th, 9th, 29th-31st for the 1st-day forecast, as well as missing data for October 5th, 10th, 30th-31st for the 2nd-day forecast. It was felt that this missing data would prevent consistent comparisons with monthly MALAPS and Satellite data being made.

7.1 Daily results

Daily results for solar exposure averaged over the whole of Australia are shown in fig. 42. It is evident that ACCESS-A gives a much better overall agreement with the satellite data. The MALAPS forecast does provide better agreement between October 10th-14th.

7.2 Daily results - spatial analysis

Spatial plots of solar exposure for selected days are shown in figs 43 and 44. Results for the 1st-day forecasts are shown in fig. 43, with some 2nd-day forecast results presented in fig. 44.

The comparison of the 1st day ACCESS-A and MALAPS forecast for October 3rd is shown at the top of fig. 43. While the predicted cloud coverage from both NWP models is similar, the optical depth from ACCESS-A is far closer to the Satellite estimate. It was shown earlier in § 3 that the MALAPS model consistently under predicts the amount of solar attenuation by producing clouds that were too optically thin. The ACCESS model produces an optically thicker cloud field, and therefore the forecast exposure field has better agreement with the satellite data. The PDF shape for the ACCESS-A forecast has much better agreement with the Satellite data. In particular, the shape of the long PDF tail for the ACCESS data suggests excellent agreement with the lower exposure values estimated by the satellite algorithm.

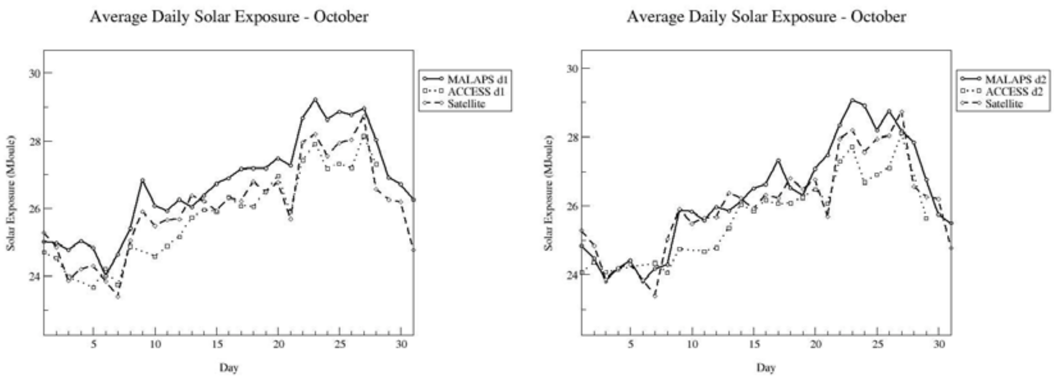

Fig. 42 Plots of daily solar exposure averaged over continental Australia for 1st-day ACCESS and MALAPS forecasts (left) and 2nd-day forecasts (right). Note that the ACCESS data is missing values at certain days. The suffixes 'd1' and 'd2' refer to 1st and 2nd day forecasts respectively.

The ACCESS model performed slightly worse than the MALAPS model for the 1st-day forecast on 18th October. Although the cloud coverage produced by the ACCESS model is a good estimate of the observed cloud pattern, the cloud is slightly too thick, giving a lower overall value of spatially-averaged solar exposure. Although the MALAPS model produces less cloud than was observed by the satellite, the averaged exposure is closer to the satellite value.

The cloud pattern over Australia on the 21st October was dominated by a large frontal band located in Western Australia. Both NWP models provide good estimates of cloud coverage; however the ACCESS model gives more accurate estimates of cloud thickness producing excellent agreement with the satellite exposure values. The PDFs for the ACCESS and satellite data also show good agreement. The MALAPS model produces cloud that is too optically thin, producing forecast exposure values that are too high.

The results for the 2nd-day forecasts are shown in fig. 44. On the 9th of October, there were two separate regions of cloud located in northern Queensland and northern Western Australia. The ACCESS model predicted the cloud coverage very well; however the cloud thickness was too large, causing lower forecast values of solar exposure when compared to the satellite. The MALAPS forecast cloud coverage was greater than the observed coverage, with MALAPS predicting large amounts of cloud over south-east Australia. However, as the MALAPS cloud is thinner than that observed from the satellite, the average exposure value for the MALAPS model is in better agreement with the satellite. This is an example of complementary errors giving an overall better result.

The results for 17th October provide another example of the ACCESS model giving a better estimate of both the cloud coverage and cloud thickness when compared to the MALAPS model.

The forecast results for the 21st October presented in fig. 43 for the 1st-day forecast are repeated in fig. 44 for the 2nd-day forecast. For this particular cloud feature, both models were able to give accurate forecasts of cloud coverage two days in advance. However, the ACCESS model was able to give accurate forecasts of cloud thickness as well, giving good agreement with the satellite estimates of exposure. These results suggest that the ACCESS model is able to provide better estimates of optical thickness. Indeed, the trend for ACCESS is to slightly over predict the amount of solar attenuation by producing clouds that are optically thicker than those estimated by the satellite.

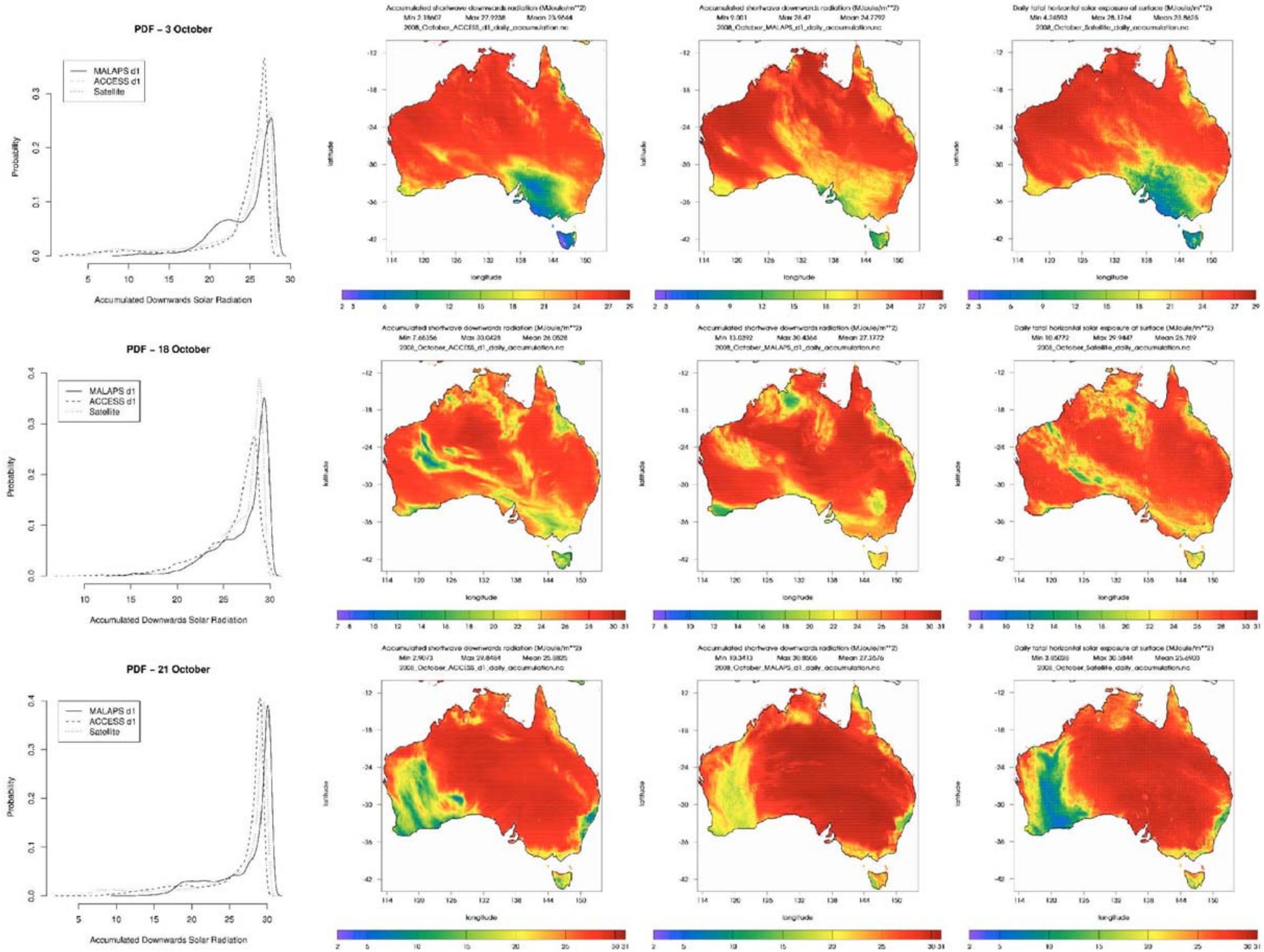

Fig. 43 Spatial analysis of daily solar exposure for October 3 (top), October 18 (middle) and October 21 (bottom). From L to R: PDF distributions for MALAPS and satellite data, colour plots for MALAPS 1st day forecast, MALAPS 1st day forecast and satellite data

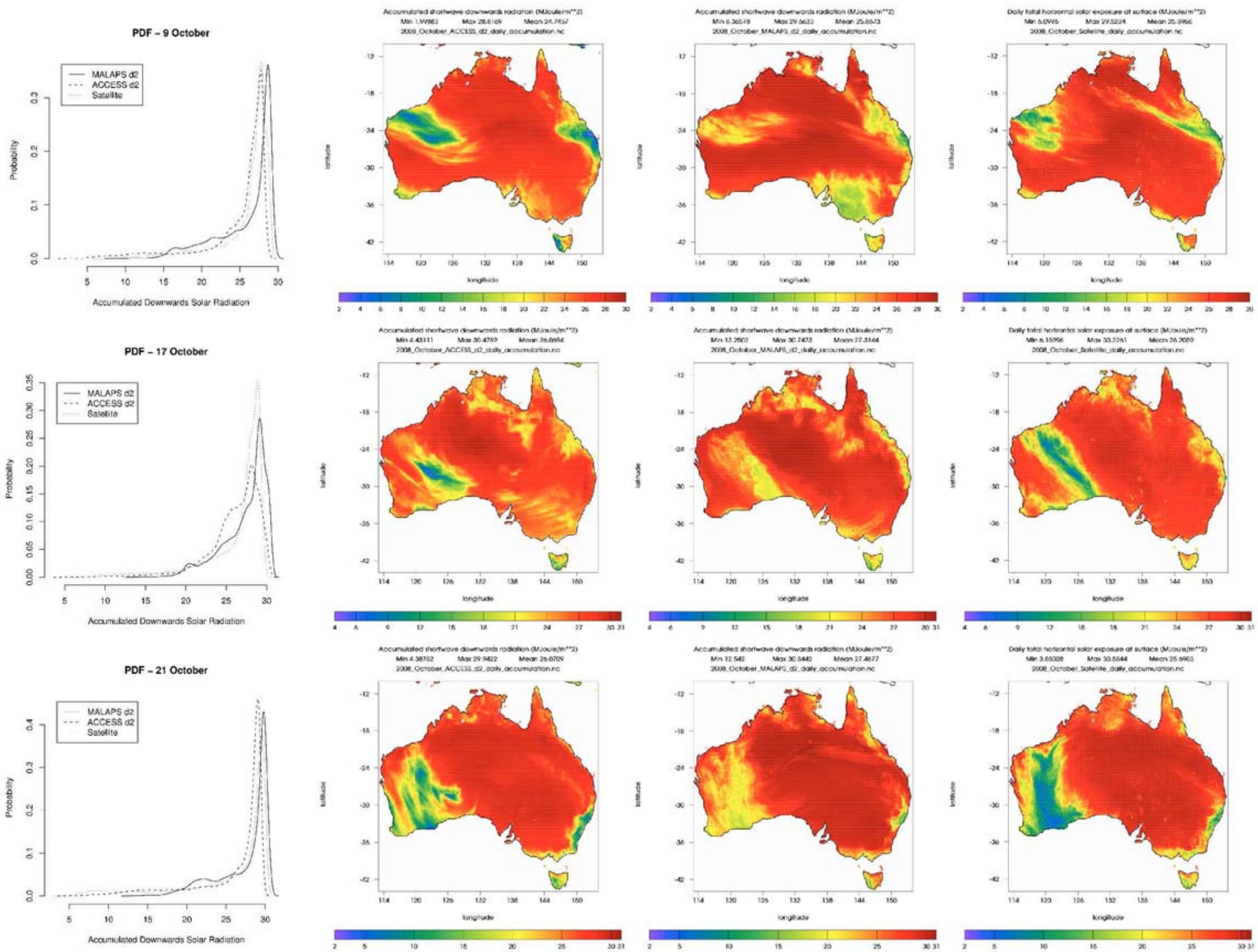

Fig. 44 Spatial analysis of daily solar exposure for October 3 (top), October 18 (middle) and October 21 (bottom). From L to R: PDF distributions for MALAPS and satellite data, colour plots for MALAPS 1st day forecast, MALAPS 1st day forecast and satellite data

7.3 Ground-based measurements - monthly results

Monthly averages for October at each ground measurement station were extracted from the ACCESS-A data. As mentioned previously, these results are to be used with caution as there are four missing days from the ACCESS October results which could potentially skew the results. The results for the 1st and 2nd day ACCESS forecasts are shown in tables 12 and 13 respectively.

Table 12 *Monthly averaged exposure values for MALAPS and ACCESS 1st-day forecast data compared with satellite data extracted at various site locations in Australia.*

Site	MALAPS	ACCESS	Satellite	Site	Δ Site		
					MAL.	ACC.	Sat.
Alice Springs	27.53	28.75	27.59	26.55	0.98	2.21	1.04
Darwin	27.35	24.84	25.94	22.73	4.63	2.12	3.22
Cape Grim	20.19	17.38	21.21	19.16	1.03	-1.78	2.05
Wagga Wagga	24.87	23.65	24.74	24.44	0.43	-0.79	0.30
Broome	27.10	26.83	27.96	25.81	1.29	1.02	2.15
Melbourne Airport	20.97	19.32	24.14	17.95	3.02	1.38	6.19
Rockhampton	25.71	23.23	24.95	23.31	2.39	-0.08	1.64
Adelaide	22.54	22.46	24.26	22.73	-0.19	-0.27	1.53

The ACCESS model shows significant improvement for Melbourne Airport and Rockhampton for both forecast days, with the 1st-day forecast showing some improvement in Darwin. The 2nd-day ACCESS forecast gave better results at Wagga Wagga. Surprisingly, the ACCESS model is worse for Alice Springs. Further analysis is required to determine if this is a systematic error. For the remaining sites, there was no clear trend.

7.4 Ground-based measurements - daily results

Plots of daily exposure values at each site for the ACCESS and MALAPS models are shown in figs 45 and 46. The 1st-day forecasts are presented in fig. 45 with the 2nd-day forecasts shown in fig. 46. Both figures also have the site-based values of exposure.

Examining the results for Alice Springs shows that the ACCESS model exhibits almost exact agreement with the site-based data for the majority of the month. However, from October 4th - 9th the ACCESS model performs very poorly and fails to forecast the large changes in observed exposure.

The improved performance of the ACCESS model for Melbourne can be attributed to the model's better ability to forecast the large changes in observed exposure which occur at the end of the month. The performance of the 1st-day ACCESS forecast between October 23rd27th is impressive, achieving almost exact agreement with the observed data in a period with highly variable day-to-day exposure.

Table 13 *Monthly averaged exposure values for MALAPS and ACCESS 2nd-day forecast data compared with satellite data extracted at various site locations in Australia.*

Site	MALAPS	ACCESS	Satellite	Site	Δ Site		
					MAL.	ACC.	Sat.
Alice Springs	28.04	28.56	27.59	26.55	1.50	2.01	1.04
Darwin	25.56	25.16	25.94	22.73	2.84	2.44	3.22
Cape Grim	20.73	17.99	21.21	19.16	1.57	-1.17	2.05
Wagga Wagga	25.71	24.30	24.74	24.44	1.27	-0.14	0.30
Broome	26.72	26.80	27.96	25.81	0.91	0.99	2.15
Melbourne Airport	23.42	19.03	24.14	17.95	5.47	1.09	6.19
Rockhampton	24.45	23.40	24.95	23.31	1.13	0.09	1.64
Adelaide	23.13	22.51	24.26	22.73	0.40	-0.22	1.53

Similar trends are observed in Wagga Wagga, with the ACCESS model showing a marked improvement over the MALAPS model in being able to forecast very cloudy days.

The performance of the ACCESS model in Darwin shows that it still misses some of the daily changes in solar exposure. However, the observed trend for the MALAPS model to continually over predict the site data is absent in the ACCESS results.

The differences between the ACCESS and MALAPS models at the other sites (Cape Grim, Adelaide, Broome and Rockhampton) are too small to draw any definitive conclusions

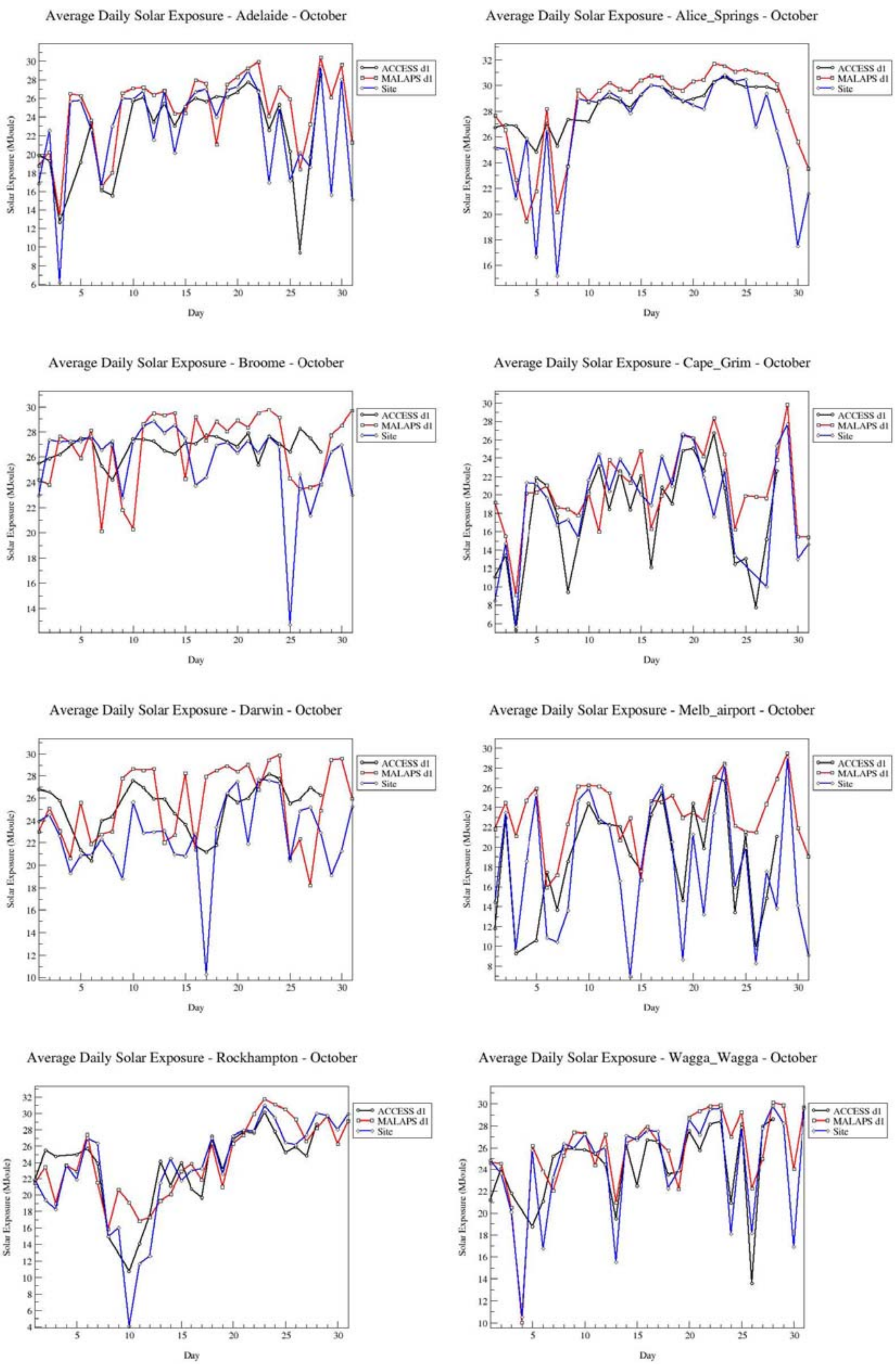

Fig. 45 Plots of daily solar exposure for October at selected sites within Australia. The ACCESS and MALAPS 1st-day forecasts are shown.

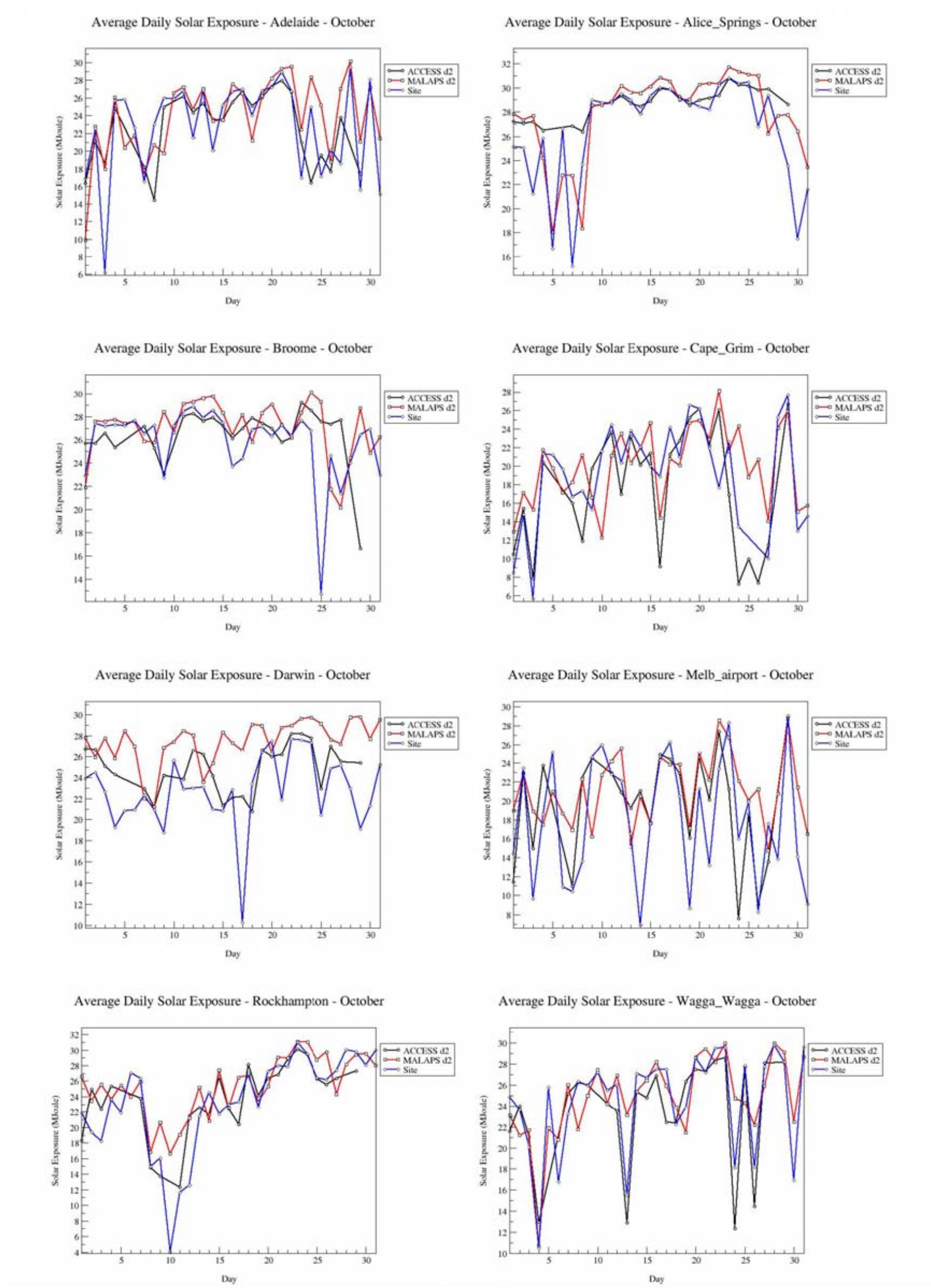

Fig. 46 Plots of daily solar exposure for October at selected sites within Australia. The ACCESS and MAPLAPS 2nd-day forecasts are shown.

7.5 Ground-based measurements - hourly results

Selected days at various sites were chosen for hourly analysis, as per the procedure previously performed in § 5.3 for the operational models. The first day chosen was the 7th of October at Alice Springs. This was one example where the ACCESS model performed much worse than the MALAPS model. Results for the MALAPS and ACCESS model are shown below in table 14 and fig. 47.

7.5.1 Alice Springs - October 7th

Table 14 *Comparison of accumulated solar exposure between the 1st-and 2nd-day ACCESS and MALAPS forecast against site data for Alice Springs on October 7th.*

Date	MALAPS		ACCESS		Site	MALAPS		ACCESS	
	1stday	2ndday	1stday	2ndday		Δ1st	Δ2nd	Δ1st	Δ2nd
7th	20.17	22.76	25.65	26.91	15.19	4.98	7.57	10.46	11.72

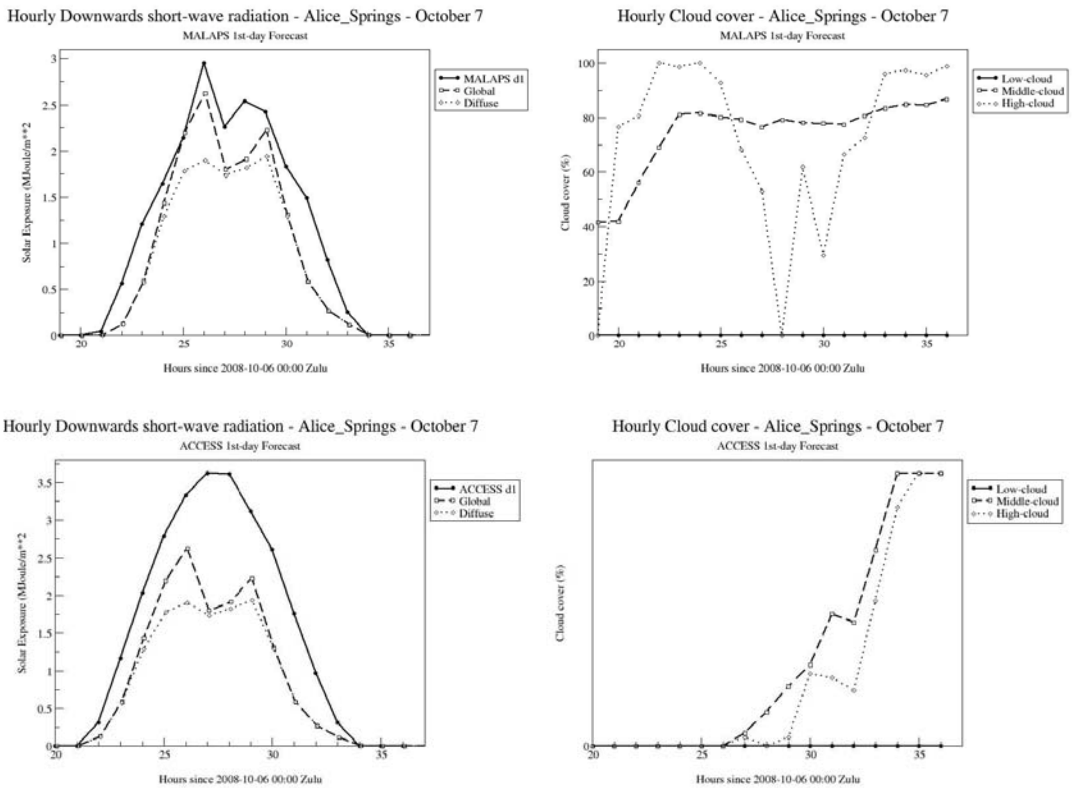

Fig. 47 Analysis of hourly change in computed exposure and cloud cover for MALAPS 1st-day forecast (top) and ACCESS 1st-day forecast (bottom) for Alice Springs on October 7. Site-based exposure values are super-imposed on the exposure plot. There were no observed cloud features.

The results of fig. 23 suggest that the differences in the computed exposure between the two models can be attributed to differences in the computed cloud coverage. The MALAPS model predicts significant amounts of middle and high cloud through most of the day, whereas the ACCESS model predicts cloud cover only in the afternoon.

Unfortunately there are no cloud observations recorded for this day. The observed values of direct and diffuse exposure suggest that cloud cover was present during the day. However the lack of observed cloud data makes it difficult to determine if the MALAPS model performs better because of an accurate cloud field prediction, or if the accurate forecast is due to complementary errors. That is, does the MALAPS model produce a better forecast by incorrectly calculating the radiance through an incorrect cloud field?

7.5.2 Darwin - October 17th

The results for the MALAPS and ACCESS models for Darwin on October 17th are shown in table 15 and fig. 48. The observed solar exposure data suggests the day was dominated by diffuse radiation, and the observed cloud fields show consistent coverage of altocumulus and cumulus during the day.

Table 15 *Comparison of accumulated solar exposure between the 1st-and 2nd-day ACCESS and MALAPS forecast against site data for Darwin on October 17th.*

Date	MALAPS		ACCESS		Site	MALAPS		ACCESS	
	1stday	2ndday	1stday	2ndday		Δ1st	Δ2nd	Δ1st	Δ2nd
17th	27.90	26.53	21.16	22.17	10.27	17.63	16.26	10.89	11.90

Both the NWP models under predict the cloud coverage for this day. As the ACCESS model predicted slightly more cloud cover, the daily exposure value was closer to the observed value. What is interesting about this day is that the ACCESS exposure takes a significant drop at hour 28 which is independent of any forecast cloud amount.

7.5.3 Wagga Wagga - October 24th

The results for the MALAPS and ACCESS models for Wagga Wagga on October 24th are shown in table 16 and fig. 49. This provides an excellent example of the improvements that the ACCESS model can provide.

Table 16 *Comparison of accumulated solar exposure between the 1st-and 2nd-day ACCESS and MALAPS forecast against site data for Wagga Wagga on October 24th.*

Date	MALAPS		ACCESS		Site	MALAPS		ACCESS	
	1stday	2ndday	1stday	2ndday		Δ1st	Δ2nd	Δ1st	Δ2nd
24th	27.03	24.85	20.75	18.10	12.20	14.83	12.65	8.55	5.90

Both NWP models forecast cloud fields made of predominantly middle and high cloud. The MALAPS model forecast almost 100% coverage of high cloud throughout the day, with additional middle cloud in the afternoon. The ACCESS model also forecast middle and high-cloud, but in lower amounts. ACCESS predicts high cloud in the morning, tapering off over the course of the day, while middle cloud increases in the afternoon.

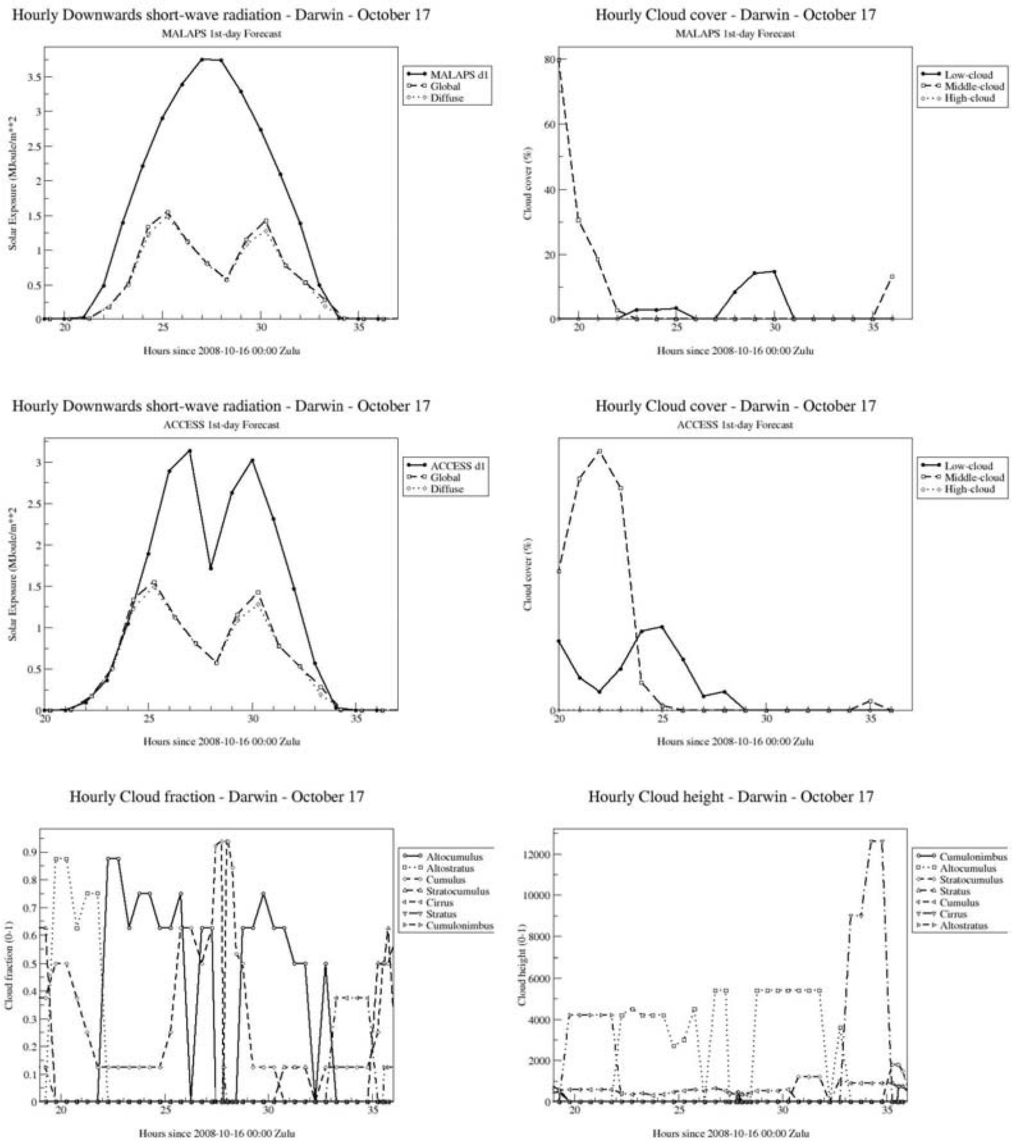

Fig. 48 Analysis of hourly change in computed exposure and cloud cover for MALAPS 1st-day forecast (top) and ACCESS 1st-day forecast (middle) for Darwin on October 17. The observed cloud properties are also shown (bottom).

The exposure results show that despite all the cloud cover predicted by the MALAPS model, there is too much irradiance reaching the surface. This is another example of the well known flaw in the MALAPS model, in that middle and high-clouds are too optically thin (i.e. transparent to incoming solar irradiance).

Although the ACCESS model predicts less cloud coverage, the more accurate computation of optical thickness for the middle and high-clouds gives a more accurate value of solar exposure for this day.

Unfortunately, there was no observed cloud data available for this day, so it is difficult to determine what clouds actually existed in reality.

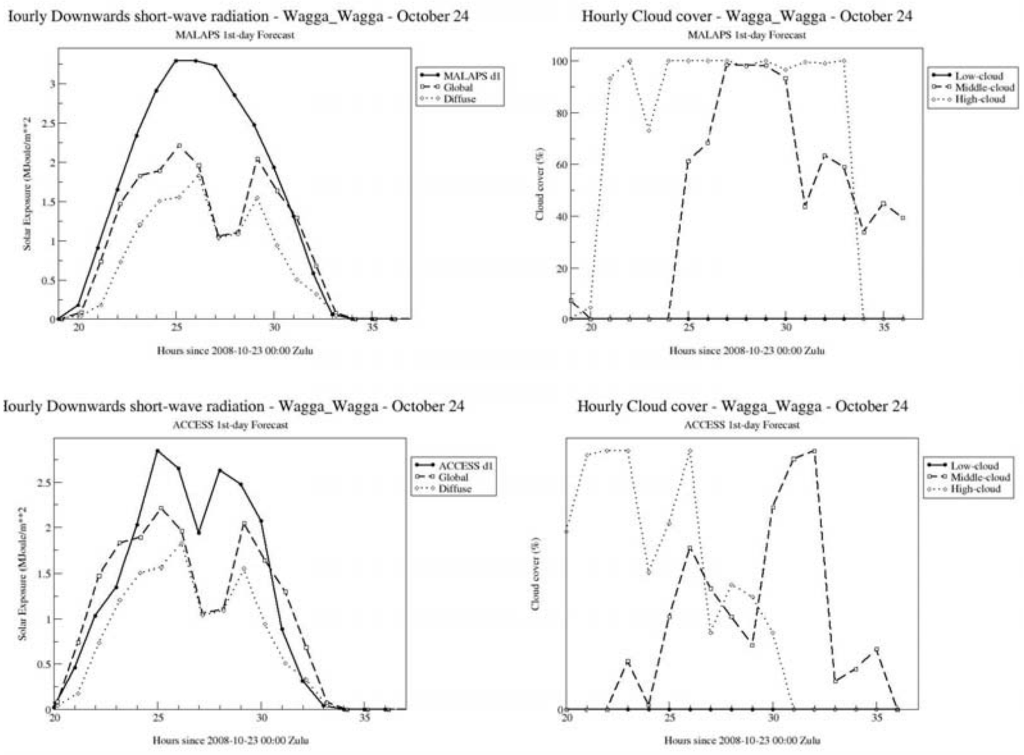

Fig. 49 Analysis of hourly change in computed exposure and cloud cover for MALAPS 1st-day forecast (top) and ACCESS 1st-day forecast (bottom) for Wagga Wagga on October 24. Site-based exposure values are super-imposed on the exposure plot. There were no observed cloud features.

7.6 Section summary

The analysis procedure used to assess the existing MALAPS model was repeated for the new ACCESS model for October 2008. The ACCESS model showed consistent improvements throughout the month. Analysis of the exposure plots over the whole Australian continent for selected days showed that the ACCESS model provides much better estimates of attenuated solar exposure through clouds. Whereas the MALAPS model consistently over predicted the exposure value in cloudy regions, the ACCESS model gave much better results compared to the satellite estimate. Indeed, the ACCESS model tended to produce slightly too much solar attenuation through cloud fields. In other words, ACCESS tends to create clouds that are too thick when compared to satellite cloud optical thickness estimates.

Site-based analysis of the ACCESS forecasts confirmed that the ACCESS model gave superior performance in the tropics compared to the MALAPS model. Significant improvements were also observed at Wagga Wagga and Melbourne. In particular, the day-to-day ACCESS results at these sites showed that the model was able to simulate the passing of large cloud bands, and hence replicate the large day-to-day variance in solar exposure. It is presumed that the new prognostic cloud scheme used by the ACCESS model is responsible for these improvements.

Hourly analysis showed that the ACCESS model gave much better estimates of predicted solar attenuation through high cloud fields, whereas the MALAPS model on the same day and site treated these high cloud fields as optically transparent.

8 FURTHER WORK

8.1 Site-based cloud analysis

The site-based cloud analysis has been carried out for a few days at selected locations, and some trends have been identified. Further analysis at other sites and times of the year would yield more information. Fig. 50 shows the MALAPS 1st-day forecast at Broome and Darwin. Clearly, the results at Darwin show significant errors throughout the month. Further analysis would determine if this is related to cloud parameterisation or errors in predicted cloud cover. There is also a possibility that the problem is due to the presence of aerosols (airborne particles) which are known to affect Darwin at some times of the year and which are not treated by the current NWP models or satellite processing.

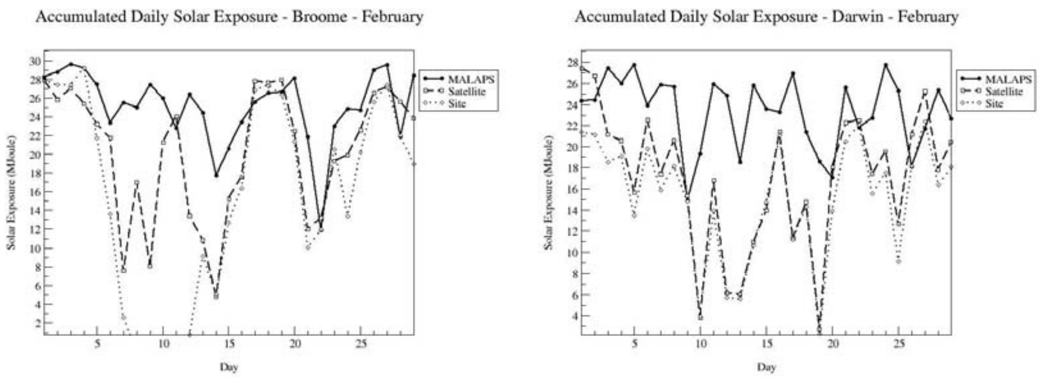

Fig. 50 Comparison between the 1st-day MALAPS forecast against satellite and site data for Broome (left) and Darwin (right) in February 2008.

Such work also has to be continued for the ACCESS model data. It is difficult to find days where the predicted cloud fields from the ACCESS and MALAPS forecasts are similar enough to eliminate any discrepancy in the cloud field as a source of error in the computed exposure. Only by locating days where the ACCESS and MALAPS forecast cloud fields are similar can changes to the ACCESS radiation calculations be assessed.

Another aspect of cloud analysis would involve comparison of daily satellite cloud fields against the NWP cloud fields. This would help determine how accurately the NWP code can forecast particular cloud types, in particular the example for satellite exposure values for Melbourne in May which were consistently worse than the NWP forecasts.

This analysis would also determine the anomaly that the NWP gives better exposure forecasts in May, despite producing non-existent cloud cover, according to the ground-based observations. It would also help to fill in the days when there are no observed clouds, despite large amounts of diffuse radiation being recorded on the ground.

8.2 Further ACCESS analysis

Only one month of ACCESS data has been analysed. The project has shown that solar exposure is a seasonal quantity which has substantial variation over the course of the year. The MALAPS results showed that the forecast accuracy also varied greatly over the course of the year, especially in the tropics.

Only by repeating the analysis for a year's worth of ACCESS results can an assessment of the new model's ability to forecast solar exposure be accurately performed.

In addition to the validation against satellite and ground data, the synoptic analysis presented earlier in § 4.1 also needs to be repeated for ACCESS results. This would allow assessment of the improvements in the model's cloud scheme to provide better forecasts of major cloud bands.

9 CONCLUSIONS

Analysis of the NWP predictions for solar exposure was conducted using two of the Bureau's current operational NWP models of differing spatial resolutions, for one, two and three day forecasts. This analysis was performed for the 2008 Calendar year. Comparison with satellite measurements showed that the monthly averaged forecast exposure over Australia showed good agreement with satellite data, however the day-to-day exposure values showed some consistent errors. Errors in forecast exposure were usually attributed to incorrect computation of cloud optical properties in the tropics during summer, as well in south-eastern Australia and Tasmania. Other errors were attributed to incorrect cloud coverage being forecast across continental Australia, although these were less frequent.

Computation of the probability-density-functions (PDFs) for the satellite and NWP forecast data were performed for the whole of Australia, as well as for three latitude zones. These showed that the computed monthly averaged exposure was continually over predicted in the tropics in the summer months, and continually over predicted for south-eastern Australia for the whole year. The computed clouds in these regions were too optically thin and did not produce enough attenuation of the solar exposure. Clouds in the summer tropics are often dominated by local convective clouds that occur during the day. Clouds over south-east Australia are often created due to orographic lifting around the Great Dividing Range, and indeed many of the errors in the minimum value of the exposure are seen in the vicinity of these ranges. Of course it is possible that the satellite algorithm may be incorrect over high topography due to the presence of snow etc. This issue also needs further investigation.

The spatial analysis suggested that the errors in the summer tropics were due to the NWP code being unable to predict the formation of convective clouds during the day.

Comparison with site-based exposure observations was conducted at eight locations across Australia. This analysis was conducted on a daily and hourly basis. At the time of writing, site data was available for the period January-July 2008. The site-based exposure measurements echoed the findings from the spatial analysis against satellite data, i.e. the NWP values for exposure were often greater than the site values, especially in the tropics during summer. The daily analysis at lower latitudes showed that the NWP forecast could track the qualitative behaviour of the site-based observations, but it would often over predict the exposure value for days of heavy cloud cover, particularly for high level cloud. During the winter months, the NWP codes often showed better estimates of exposure than the satellite data.

Hourly analysis at a few sites showed that the NWP codes were able to predict the solar exposure accurately through low-level clouds (e.g. Cumulus and Stratocumulus), provided that the forecast cloud coverage was accurate. Results obtained at Rockhampton, Melbourne and Alice Springs suggest that the NWP codes struggle to predict solar exposure through high clouds (e.g. Altocumulus and Altostratus). These higher clouds are formed by ice-crystals and have very different radiation scattering behaviour compared to lower, cooler clouds which are formed by water droplets. Preliminary analysis suggests that the NWP radiation code predicts too much radiation transmission through these high clouds, i.e. they are too optically thin, and it is these errors in high cloud radiation transmission that are responsible for the over prediction of solar exposure.

The analysis of the NWP code has shown that it struggles to produce accurate forecasts of solar exposure in some areas of Australia. In particular, tropical regions during the summer, as well as regions along the south-east coast of Australia close to the Great Dividing Range.

However, it should be noted that these areas are poor locations for any large-scale solar power plant, because the same factors that create poor NWP predictions of exposure (i.e. cloud formations created by local effects such as convection or orographic lifting) are the same factors that would discourage a solar power plant from being built in these regions.

In the middle latitudes of Australia, the NWP has shown the ability to provide good estimates of solar exposure. The PDFs of predicted and satellite exposure for the middle latitude show excellent agreement throughout the year. Additionally, the agreement of the NWP with the site-based observations at Adelaide was the best of all the locations, with Wagga Wagga and Alice Springs also showing good agreement.

Therefore, the current NWP system is able to provide useful forecasts of solar exposure at likely solar power plant locations. Preliminary analysis of the ACCESS NWP system (which should become operational later in the year) shows that this provides even more accurate predictions of solar exposure, as it is able to provide more accurate estimates of solar attenuation through high cloud types.

10 ACKNOWLEDGMENTS

We gratefully acknowledge support from the Department of Resources, Energy and Tourism (DRET) under the Wind Energy Forecasting Initiative for their support of this research.

The authors are very grateful to Ian Grant, Ian Muirhead and Zhian Sun for their detailed and constructive reviews and comments.

11 BIBLIOGRAPHY

Grant, I.F., Jones, D., Wang, W., Fawcett, R. and Barratt, D. 2008 Meteorological and remotely sensed datasets for hydrological modelling: A contribution to the Australian Water Availability Project, CAHMDA-III *International Workshop on Hydrologic Prediction: Modelling, Observation and Data Assimilation, Melbourne, Australia*, 9-11 January 2008.

Grant, I. & Muirhead, I. 2009 New Spatially Explicit Solar Radiation Climatologies for Australia. In Solar 09, *The Annual Conference of the ANZSES, Australian and New Zealand Solar Energy Society, Townsville, Queensland, Australia*, pp. 23–51. Springer.

Weymouth, G. & Le Marshall, J. 2001 Estimation of daily surface solar exposure using GMS-5 stretched-VISSR observations: the system and the basics. *Aust. Met. Mag.*, 50, pp. 253-278.

The Centre for Australian Weather and Climate Research is a partnership between CSIRO and the Bureau of Meteorology.