Tropospheric moisture profiles from
digital IR satellite imagery: system
description and analysis/forecast impact

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A system for deriving tropospheric moisture profiles from GMS infrared (IR) satellite imagery is described. Clouds are classified into nineteen categories depending on cloud amount, height and standard deviation of cloud top temperature over 50 km radius circles. Dew-point depression profiles for each category are assigned by matching co-located radiosonde data. Examples of limited area numerical analysis and prognosis impact are presented.

Introduction

The paucity of data over the Australian region has long been recognised as a major limitation to short-term forecasting. Subjective interpretation of satellite imagery has for some years been an important component of the Australian National Meteorological Centre (NMC) objective analysis system (Guymer 1978). Since FGGE, temperature retrievals from orbiting satellites (Kelly et al. 1983) and cloud motion vectors (Davidson and McAvaney 1981) have provided significant alleviation of this problem at synoptic scales.

Concurrent with this improved data base have been increases in local computing power which have allowed increased horizontal and vertical resolutions, and improved parametrisations of the physical processes in numerical weather prediction models (Leslie et al. 1985). This in turn has allowed more detailed weather-related information to be obtained from these forecast models (e.g. Mills and Leslie 1985).

A significant deficiency in the Australian NMC mesoscale analysis/forecast system is the poor quality of the moisture analysis caused by the lack of data. At 0000 UTC the radiosonde observing network (see Fig. 1) is only sufficient to resolve broadscale moisture features; it is insufficient to define small-scale features, or even the precise location of boundaries of major cloudbands. At 1200 UTC (see Fig. 1) the situation is even worse. Over the ocean areas, some limited information is provided by data from polar-orbiting satellites which are received via the Global Telecommunications System (GTS), but these data are not used operationally because of problems with data quality control. This will be alleviated in the future by local direct readout of satellite data (Kelly et al. 1983) and improved physical retrieval algorithms (Smith et al. 1985). Mills (1983), recognised

![Fig. 1 Locations of radiosonde stations in Australia. Dots are stations at 0000 UTC only, circled dots for 0000 and 1200 UTC.](image-url)
Encouraged by the Mills case study, and also by Japanese success with a system of specifying humidity profiles from Geostationary Meteorological Satellite (GMS) imagery (Kanamitsu personal communication), an objective system of relating infrared black-body temperature statistics to tropospheric moisture profiles has been developed for the Australian region. Recently a system (Benoit and Koclas 1984) using geostationary satellite imagery to provide bogus data to enhance moisture analyses has also been developed in Canada.

The next section of this paper describes the development of the moisture retrieval scheme, while the following section provides examples of the impact of these data on objective analyses and numerical forecasts.

**The moisture retrieval system**

Satellite cloud imagery from the series of Japanese GMS satellites has been received in Australia since the first satellite was launched in 1977. In routine use, infrared (IR) images are received 8 times per day, with more frequent data available during severe weather events such as tropical cyclones.

However, due to computing limitations, only 0000 UTC IR digital data south of 1°N were archived prior to 1985. Since 1 January 1985 3-hourly digital data over the same domain have been archived. These data are in the form of mean cloud top (or surface) temperature over approximately 2.5 km x 2.5 km areas (pixels). These digital IR images archived for the calendar-year 1984 provided the dependent satellite data for the development of the moisture retrieval algorithm. The Australian region analyses (Seaman et al. 1977) archived operationally by the NMC, and the raw radiosonde temperature and humidity profiles from each of the stations shown in Fig. 1 archived by the Bureau's National Climate Centre provided the remainder of the dependent data.

The premise on which the development of the moisture retrieval algorithm was based was that a statistical analysis of the equivalent black-body temperature of each pixel (which will be regarded as the cloud top temperature (CTT)) in an area co-located with a radiosonde ascent could be used to classify the cloud depth, amount and type in that area, and that this cloud classification could be related to the dew-point depression profile of the associated radiosonde ascent.

The CTT analysis program used by Lajoie and Butterworth (1984) was adapted to compare the CTT of each pixel within a 50 km radius circle surrounding each radiosonde site with the temperatures at the pixel location as interpolated from the NMC archived objective analysis. The cloud top, as represented by the CTT of that pixel, was then assigned to be within one of the layers defined by the analysis pressure levels; i.e. to the layers surface-850 hPa, 850-700 hPa, 700-500 hPa, 500-300 hPa, and above 300 hPa. The screen-level temperature and dew-point analysis system of Keenan et al. (1986) was used to define a surface temperature. For each layer and for the whole troposphere, the fractional pixel count (i.e. the cloud amount), the mean CTT, and the standard deviation of the CTT of the cloudy pixels within that layer were then determined. This provided a data set of CTT statistics and co-located radiosonde dew-point depression profiles on a monthly basis for one calendar-year, containing some 8500 items.

Rather than derive statistical regression relationships between the cloud and the radiosonde observations, the data were stratified into categories based on three a priori criteria. These criteria were based on the intuitive expectation that the amount, depth, and type of cloudiness is strongly related to the characteristics of the moisture profile of the environment. The first classification criterion was the layer of maximum cloudiness, the second was whether the cloud amount in the layer covered more or less than 50 per cent of the area, and the third was whether the major cloud layer was cumuliform or stratiform. This final cloud-type assignment was based on the standard deviation of the CTT within the layer, with a standard deviation greater (less than) 3.5°C indicating cumuliform (stratiform) cloud. If the layer of maximum cloud was below 850 hPa, no cumulus category was assigned and if cloud amount was less than 20 per cent, the sounding was designated 'clear'. Accordingly nineteen categories were assigned: amount (scattered, broken) by depth (5 layers) by type (cumuliform, stratiform), plus one 'clear' category, less two categories since no cumulus category was assigned below 850 hPa.

The dew-point depression profiles associated with each of those 19 categories were then averaged to provide a mean dew-point depression profile from 850 hPa to 300 hPa for each category. As the GMS data do not contain any information below the cloud layer, it was decided to use the Keenan et al. (1986) surface temperature and dew-point analyses to provide fields of dew-point depression at the lowest level.

The data were not stratified in space, although this is an obvious avenue for further investigation. However the authors feel that the use of dew-point depression as a moisture parameter will reduce the geographical dependence of the system. The data were stratified into summer (October-March) and winter (April-September) classifications, but very little difference was found between the two. For this reason we will only present annual mean dew-point depression profiles for each of the 19 cloudiness categories. These are shown in Fig. 2, together with the corresponding cloud classification and the top of the layer of maximum cloudiness. Associated with each profile is whether the cloud was cumuliform (Cu) or stratiform (STF), and whether the cloud amount was greater (BKN) or less (SCT) than 50 per cent. The bracketed numbers indicate the number of cases selected in each category. In general terms, the profiles seem compatible with their cloud groups: moisture is greater below cloud top level, there is more moisture for broken than for scattered cloud categories, and there is more lower (upper) level moisture for cumuliform (stratiform) categories.

The application of the system for a particular analysis
Fig. 2  Dew-point – depression profiles for each of the 19 cloud categories, together with the type of cloud (cumuliform (Cu) or stratiform (STF)) whether greater (BKN) or less (SCT) than 50% cloud cover. Bracketed numbers indicate the number of matchups in each category, while 'MAX' indicates the pressure layer in which the maximum cloud amount resides.
time then entails the determination from the GMS image of cloud characteristics at latitude-longitude points, and the assignment of the corresponding cloud category and dew-point depression profile at each of these points. The actual retrieved moisture observations are then determined from the dew-point depression profile and the analysed temperatures at each point.

Using this system, moisture profile data have been generated on a 2° x 2° latitude-longitude grid for some 20 cases to date. The domain over which the data can be determined is only limited by the available imagery. For the Australian region examples to be shown in this paper, the domain has been arbitrarily chosen to be 50°S to 10°S, 100°E to 155°E. The generated data are then treated as observations, and objectively analysed using a successive correction (SCM) scheme supplied by R. S. Seaman, with the guess field being the NMC archived analysis for that time. The observations are generally horizontally consistent over synoptic scales, and very few are rejected by the analysis system. Only in those cases when small-scale, isolated cloudiness is diagnosed from the imagery does data rejection occur. When compared with the archived analyses, the analyses using the GMS moisture data tend to show a better depiction of major cloud features, as would be expected. Examples of analyses prepared in this way are shown in Figs 3, 4, 5 and 6, where moisture analyses and GMS IR imagery are shown for two cases. On 0000 UTC 6 January 1984, (Figs 3 and 4) the re-analysed 700 hPa dew-point depression field relocates the position of a frontal cloud band over Victoria by some 7° longitude. For the case of 0000 UTC 20 May 1981, subtle changes are made in the area of the cloud mass over northeastern Australia, and over the Indian Ocean in the vicinity of the frontal cloud band.

Twenty-four hour prognoses were prepared, using the limited area numerical weather prediction model of Leslie et al. (1985) based on archived analyses, and also

Fig. 3  GMS IR satellite image for 0000 UTC 6 January 1984.
Fig. 4 Operational (top) and modified 700 hPa dew-point depression analysis (K) for 0000 UTC 6 January 1984.
on analyses which included the re-analysed moisture fields, to assess the prognosis impact of these new data. Impact was generally seen in the forecast moisture fields and in the precipitation forecasts, as would be expected, however, in a few cases when the increases in forecast precipitation were large, some improvement could be seen in the forecast mass field due to feedback from latent heat release. An example is given in Figs 7 to 10 which show the 24-hour precipitation and mean sea level pressure forecasts based on the archived and modified analyses valid at 0000 UTC 20 May 1981, together with verifying analyses. It can be seen that, although the precipitation forecast based on the archived analysis provided quite a good forecast of the rainfall maximum in far northeastern South Australia, the modified analysis produced a better forecast both of that maximum and also of the rainfall over Queensland. In addition the modified analyses gave a better indication of the development of the surface low over Queensland. We also note that the precipitation in the frontal band approaching Western Australia has also been correctly enhanced.
Fig. 6  Operational (top) and modified 700 hPa dew-point depression analysis (K) for 0000 UTC 20 May 1981.
Fig. 7 Twenty-four hour mean sea level forecasts from the operational (top) and modified analyses based at 0000 UTC 20 May 1981.
Fig. 8  Mean sea level analysis at 0000 UTC 21 May 1981.

Fig. 9  Twenty-four hour precipitation forecasts from the operational (top) and modified analysis based at 0000 UTC 20 May 1981.

Fig. 10  Twenty-four hour observed precipitation analysis valid at 9 am (0000 UTC approx.) 21 May 1981, based on the Bureau of Meteorology volunteer rainfall observing network.
Summary and discussion

A method has been developed by which bogus tropospheric moisture profile data may be generated using an analysis of cloud top temperature data from GMS IR satellite imagery. While the system is simple in concept, and the statistical scheme used is unsophisticated, it has been shown to produce analyses which subjectively appear to better reflect observed cloud features than do analyses which only use conventional data. Further, in some cases, the additional moisture detail in these analyses can impact positively on NWP model forecasts.

Further possible applications of the cloud analysis aspects of the system are to use the cloud type categorisation to define areas of deep convection, and to impose a diabatic heating rate profile into the initial state of NWP model forecasts in these areas (e.g. Danard 1985). The analysis of cloud type could also be used to refine the cloud diagnosis algorithms used in NWP models.

There is obviously a great deal of scope for refinement both of the method of derivation of these moisture profiles, and also in the method in which the data are used. For example, the dependent data base could be extended over more years which should increase the number of cases in the ‘rarer’ categories, more sophisticated statistical techniques could be used to relate the cloud statistics to the moisture profiles and the data could be seasonally or geographically stratified, and the method extended to allow for multiple cloud layers. In addition, more complex cloud recognition algorithms, such as those reviewed in WMO (1982) could be used to refine the cloud recognition criteria. In the re-analyses presented in this paper, the quantitative radiosonde data were not mixed with the cloud moisture data, and in an operational data assimilation system this would not be allowed to happen. A statistical interpolation analysis scheme, with different observational weights for radiosonde, satellite retrieval (TOVS) and cloudiness moisture data would be one approach, or perhaps a ‘pre-analysis’, using only ‘cloudy’ moisture data from the cloud analysis to define the cloud bands in the first guess field could be used. However, while all these approaches are worth investigating, and some will be tested in the near future, it has been shown that this current system can have a positive impact on objective analyses and numerical prognoses.

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References


