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MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

# The Integration of Meteorological Satellite Imagery and Numerical Dynamical Forecast Models

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# The integration of meteorological satellite imagery and numerical dynamical forecast models

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[ Plate 1 ]

Imagery of clouds, water vapour, and thermal structure as achieved in real-time from geostationary satellites can play an important role in the dynamic verification and reinitialization of numerical weather-prediction models used for short-range prediction of intense weather. By overlaying hourly interval model forecast fields over satellite imagery, the validity of the evolving forecast can be subjectively assessed and phase and amplitude errors can be diagnosed in a dynamic manner. Videographic interactive computer systems designed for the purpose should enable improved numerical weather forecasts to be made through the dynamic use of satellite imagery. This approach is demonstrated by using the Man–Computer Interactive Data Access System (McIDAS) at the University of Wisconsin for a case of the development of a cyclone over the east coast of the U.S.A.

## 1. Introduction

For future numerical prediction of localized weather, satellite imagery will play a key role in two areas: (*a*) the provision of quantitative wind estimates from tracking clouds and inhomogeneities in water vapour by using animated multispectral imagery from geostationary satellites, and (*b*) the diagnosis of model performance from quasi-continuous satellite imagery. For the latter application, the departure of the time continuity of a model variable (e.g. vertical motion) from the time continuity of cloud, water vapour, and/or thermal features displayed in imagery provided from the geostationary satellite are assumed to be indicative of the model forecast deviating from reality. For both applications, the use of a videographic interactive computer system plays a key role. It enables manual interaction for tracking cloud and water-vapour elements as displayed in an animated sequence of images on a video monitor, and for the graphic overlay of contour analyses of the output from a numerical weather prediction (NWP) model at the time of the animated satellite imagery.

The introduction of videographic interactive computer systems into forecast offices during the next several years will enable the marriage of NWP and satellite imagery for mesometerological applications. The prefix 'meso' denotes the scale of relatively small and short-lived weather systems such as fronts, convective storms and sea breezes, in contrast to the term 'synoptic', which denotes the scale of relatively large and long-lived weather systems such as major travelling low- and high-pressure systems and monsoons. In such a setting, the forecaster can view at frequent time increments (e.g. hourly) the performance of the model and use this either to correct subjectively the numerical prognosis for the future or to have the model

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reinitialized with current data and thereby generate an updated numerical forecast sequence. An example of the former is where the forecaster observes from a time sequence of model output (e.g. predicted surface pressure) and satellite imagery (e.g. visible cloud cover) that the model is moving a frontal system too quickly or slowly compared with nature. If the developing phase error appears to be linear in time, the forecaster could subjectively alter the validation time of subsequent numerical prognosis so as to conform more properly to reality. An example of the latter situation is where the forecaster sees a weather disturbance begin to develop in the satellite imagery that is not evolving in the sequence of numerical prognoses. In this case, the course of action is to analyse the current observations which would contain information on the new disturbance and then to reinitialize the forecast sequence.

The purpose of this paper is to discuss briefly the elements of such an experimental interactive numerical forecast capability being developed at the University of Wisconsin. An example is presented of the application of this capability to a case of cyclogenesis along the east coast of the United States observed during the second intensive observation period (IOP) of the Genesis of Atlantic Lows Experiment (GALE). The example demonstrates that systems that use videographic interactive computer technology for mesoscale NWP model inititalization and real-time diagnosis of model performance can and should play a key role in the mesoscale weather-analysis–forecast operation of the next decade.

## 2. The University of Wisconsin videographic computer system: McIDAS

The Man–Computer Interactive Data Access System (McIDAS) has evolved at the University of Wisconsin (Suomi *et al.* 1983) into a powerful tool for (*a*) processing and amalgamating meteorological data from *in situ* and remote sensors, (*b*) displaying contour analyses of these meteorological data over imagery from satellite, radar and lightning sensors for nowcasting applications, and (*c*) preparing and disseminating forecasts of future weather events based upon the timely and comprehensive analyses of the evolving weather patterns. Recently, a numerical weather prediction (NWP) component has been added to McIDAS. The primary purpose of the NWP component, as described briefly in the next section, is to enable four-dimensional assimilation of conventional and satellite derived moisture, wind and mass-field observations. This process will enable the production of mesoscale analyses of the atmospheric state variables and implied vertical motion, precipitation, cloud cover and other weather variables on a quasi-continuous basis. A secondary purpose is to conduct extended time numerical forecasts of mesoscale weather to demonstrate the use and potential impact of new ground-based and satellite remotely sensed wind, temperature and moisture data. As the McIDAS technology becomes an integral part of operational weather forecast offices, methods must be developed to optimize the combined use of the interactive videographic display capability, remotely sensed mesometeorological data and numerical analyses and forecasts of the atmospheric state variables.

The McIDAS also plays a key role in the generation of wind, mass and moisture observations remotely sensed from meteorological satellites (Smith *et al.* 1981*a*). For example, cloud and water-vapour winds are generated by a meteorologist viewing an animated sequence of geostationary satellite images. The operator manually selects features that are temporally consistent and, therefore, appear to be reliable tracers of atmospheric motion (see, for example, Hayden & Stewart 1987). Computer software enables accurate determination of the wind vector once the appropriate target has been selected. Quantitative interpretation of the infrared signal enables a suitable altitude assignment of the vector to be made. Figure 1, plate 1, shows an example of the cloud and water-vapour wind data for one of the initial analysis times of the case study presented in this paper.

Vertical-temperature and water-vapour soundings from both polar orbiting and geostationary satellites are achieved at the University of Wisconsin by using McIDAS to enable interactive manual control in the data editing and enhancement of the data density in meteorologically important regions (Smith *et al.* 1979, 1981 *b*). The interactive capability for producing soundings is important because a skilled meteorologist can differentiate significant fine-scale meteorological phenomena from small-scale features produced by errors in the remotely sensed data.

## 3. The CIMSS numerical weather-prediction model

The numerical weather prediction model component of McIDAS is a fifteen-level high-resolution (30–60 km) primitive equation model originally written for the Australian region (McGregor *et al.* 1978) and adapted for use in the North American region. The model has since been amended through the use of more efficient numerics, a more complete boundary layer parametrization (Leslie *et al.* 1985), the inclusion of improved numerical procedures to handle better the high topographic regions of the U.S. (Corby *et al.* 1972), and the replacement of the original parametrization for predicting convective rainfall with an improved scheme (Hammarstrand 1977).

The three-dimensional objective analysis component of the model is an evolution of the scheme developed in the Australian Numerical Meteorology Research Centre (ANMRC) by R. S. Seaman (1977) for limited area analysis over the Australian region, and adapted to the U.S. region (Mills & Hayden 1983). The model describes the atmosphere in terms of the geopotentials of constant pressure surfaces. The geopotential is the height of a surface normalized with respect to the local gravitational acceleration. The geopotential 'thickness' of a layer bounded by two pressure surfaces is proportional to the mean temperature of the air within the layer. The analysis system is based upon the calculus of variations used in an explicitly three-dimensional manner. The basic observational ingredients combined in the analysis are observed geopotential thicknesses (derived from the atmospheric temperature) of each layer and horizontal geopotential gradients either from geopotential measurements or independently derived from wind measurements and a wind law that relates the horizontal gradients of geopotential to the observed winds. Reliability weights for the analysed geopotential and geopotential gradient fields are determined on the basis of data density and standard deviation parameters which vary with latitude and level. In this way, the blended geopotential fields reflect a greater weight to the wind data in low latitudes and to the temperature information at higher latitudes.

In the forecast application of the model, the analyses are performed by using conventional and any special observations of surface and upper air pressure, temperature, moisture and wind (e.g. the special GALE observations used in the example presented in the next section), satellite-observed wind and vertical-temperature and moisture-profile data, as well as sea-surface temperature derived from the vertical atmospheric sounder (VAS) on the U.S. geostationary satellite (Bates *et al.* 1988), which is useful for establishing surface layer heat fluxes (Diak *et al.*




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1986). Because of the large-scale systematic differences often existing between the geopotential heights derived from VAS and conventional data, the VAS data are used in horizontal gradient form in the variational analysis (Diak 1988). Examples of the data coverage for the GALE observation area are shown in figure 2.

For the forecast exercise, the model is nested within the global forecast model of the National Meteorological Center (NMC) of the U.S.A.; that is, the NMC global forecast is used to provide the values of the atmospheric variables at and across the lateral boundaries of the region shown in figure 2. The boundary conditions at each model time step are produced by linear time interpolation of successive NMC 12 h global forecast fields.

## 4. An example of the use of imagery in numerical weather prediction

A demonstration of the use of satellite imagery in diagnosing the performance of a NWP model is provided here for the case of the rapid development of a cyclone off the east coast of the United States on 27 January 1986. For this case, the model was initialized at 00h00 GMT on 27 January with data obtained by the conventional surface and upper-air network and special radiosonde, dropsonde, ship, buoy, and satellite cloud and water-vapour wind data provided as part of the program (figure 2). The initial mean sea-level pressure field (MSLP) is shown in figure 3*a*, plate 1. As can be seen, at this time, there is a synoptic-scale low-pressure system centred off the Carolina coast with an intense cold front visible in the cloud imagery trailing southward across the western Atlantic and into southern Florida. During the next 24 h, the low-pressure centre intensified and moved northward across the northeastern United States and into southeastern Canada with the cold front propagating well out into the Atlantic Ocean (figure 3*e*). Inspection of the hourly interval output of the 24 h forecast sequence with respect to the cloud and water-vapour imagery from *GOES* at hourly time intervals revealed that the model successfully captured the intensification and movement of the synoptic-scale low-pressure system and the propagation of its associated cold front (figure 3*d*). However, the model failed to forecast a secondary development behind the front at about 18 h into the forecast cycle (see figure 3*b*,*c*). The new disturbance can be clearly seen in the *GOES* cloud imagery at 18h00 GMT (figure 4, plate 1).

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### Description of Plate 1

Figure 1. Satellite-derived winds from tracking inhomogeneities in clouds and water vapour for 00h00 GMT 28 January 1986. The water-vapour winds are shown overlaying 6.7 μm water-vapour imagery from the *GOES* satellite, whereas the cloud-drift winds are depicted overlaying 11.0 μm cloud imagery.

Figure 3. Mean sea level pressure (MSLP) analyses and forecasts for 00h00 GMT and 18h00 GMT 27 January 1986 and 00h00 GMT 28 January 1986. (*a*) Analysis for 00h00 GMT, (*b*) forecast for 18h00 GMT, (*c*) analysis for 18h00 GMT, (*d*) 24 h forecast for 00h00 GMT, (*e*) analysis for 00h00 GMT, and (*f*) 6 h forecast for 00h00 GMT.

Figure 4. Composite visible infrared *GOES* imagery at 18h00 GMT on 27 January 1986. The imagery reveals the development of a storm system over the Atlantic Ocean just off the Virginia–Maryland coast of the United States.

Figure 5. Original 24 h forecast and subsequent reinitialized 6 h forecast of vertical motion ($dp/dt$) at the $7\times10^4$ Pa pressure level for 00h00 GMT 28 January 1986. Negative values refer to upward motion, whereas positive values denote downward motion. The isolines of vertical motion overlay the satellite cloud imagery at the forecast validation time. The imagery has been enhanced such that the darkest regions within the otherwise white cloud mass correspond to the highest and brightest cloud cells. The 6 h forecast has benefitted from the reinitialization as explained in the text.

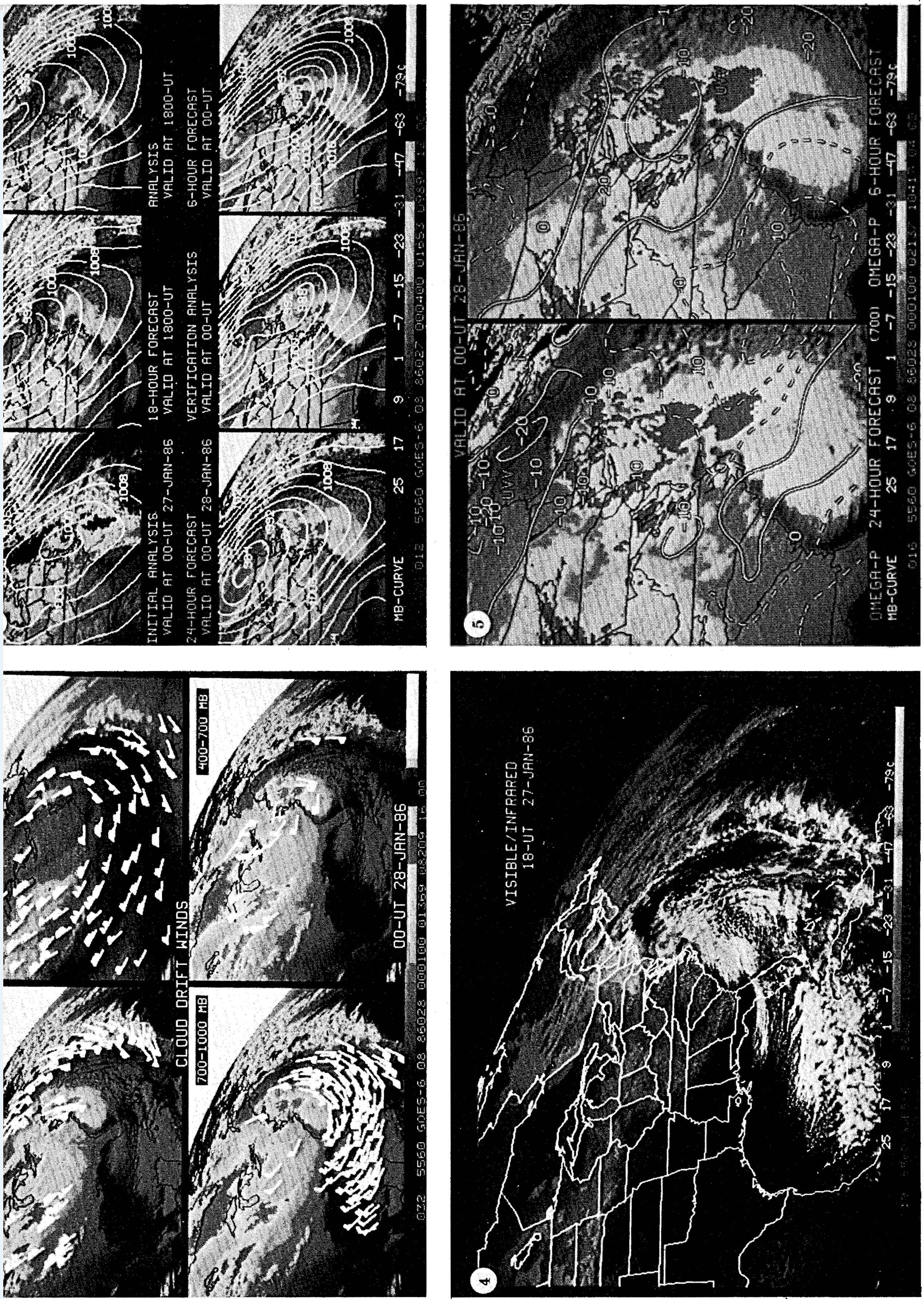


PLATE 1. For description see opposite.

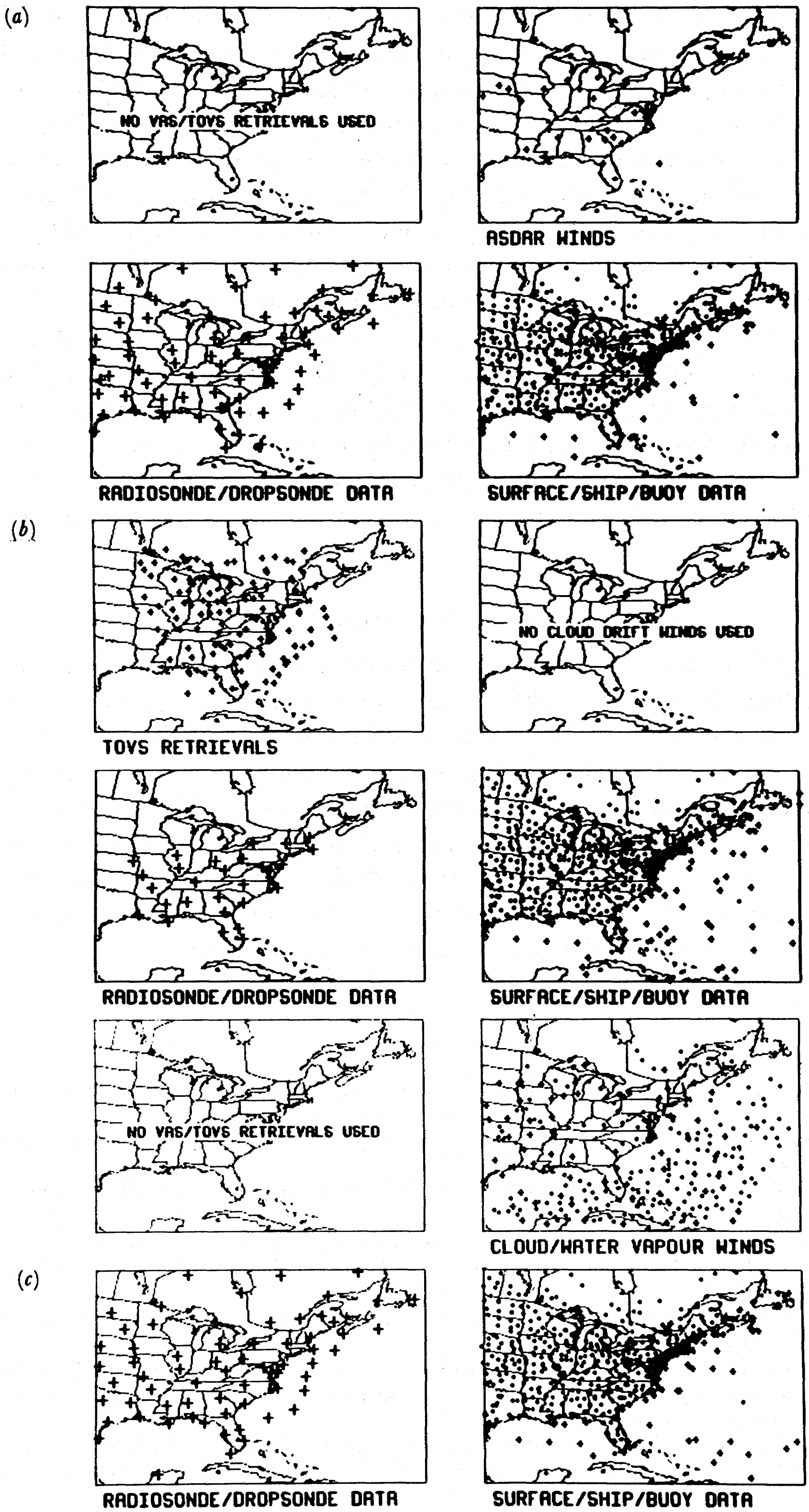


FIGURE 2. Coverage of data used in numerical analyses for (*a*) 00h00 GMT 27 January 1986 (upper four panels), (*b*) 18h00 GMT 27 January 1986 (Middle four panels) and (*c*) 00h00 GMT 28 January 1986 (lower four panels). VAS (VISSR atmospheric sounder) and TOVS (Tiros operational vertical sounder) retrievals refer to the soundings observed from the U.S. geostationary and polar orbiting satellites, respectively. ASDAR (aircraft satellite data acquisition relay) winds denote the automated wind reports received from commercial aircraft.

In a real-time application of the interactive analysis–forecast system, the user, seeing the apparent model failure, could reinitialize the model with observations available at 18h00 GMT in the hope of correcting the forecasts for subsequent times. In this case, the forecast model was reinitialized with the conventional surface observations, GALE upper-air soundings, and a large volume of upper-air temperature and moisture-profile data provided from a *NOAA*-9 satellite pass over the area of interest. These data resulted in an improved atmospheric analysis at 18h00 GMT (see figure 3*c*) with the secondary trough of low pressure diagnosed by the surface-pressure and atmospheric-temperature observations. The model, after reinitialization, forecasts the rapid intensification of the secondary low-pressure system (see figure 3*c*,*f*,*e*). The re-initialized model also forecast the upward motion within the lower troposphere along the northeast coast of the United States associated with the rapid intensification (see figure 5, plate 1). This disturbance was to produce 7–11 cm of snow in the New York area, whereas the official weather service forecast called for flurries. In summary, a significant improvement in the numerical forecast for 00h00 GMT of 28 January was achieved by the timely inclusion of conventional and satellite surface and upper-air observations at the genesis stage of small-scale cyclone development.

## 5. Conclusion

Mesoscale numerical weather prediction will benefit greatly from the use of videographic computer technology. It enables satellite imagery to be used for (*a*) the timely diagnosis of model forecast performance and (*b*) subsequent reinitialization of the forecast model with available conventional, and satellite-surface and upper-air observations. The experimental interactive numerical weather prediction system being developed at CIMSS is to serve as a prototype of operational systems for the 1990s and beyond. The example of its application to the east coast cyclone development of 27 January 1986 clearly demonstrates that such a system, utilizing a dense network of observations from the surface and from satellites, is capable of producing improved forecasts of significant small-scale weather events.

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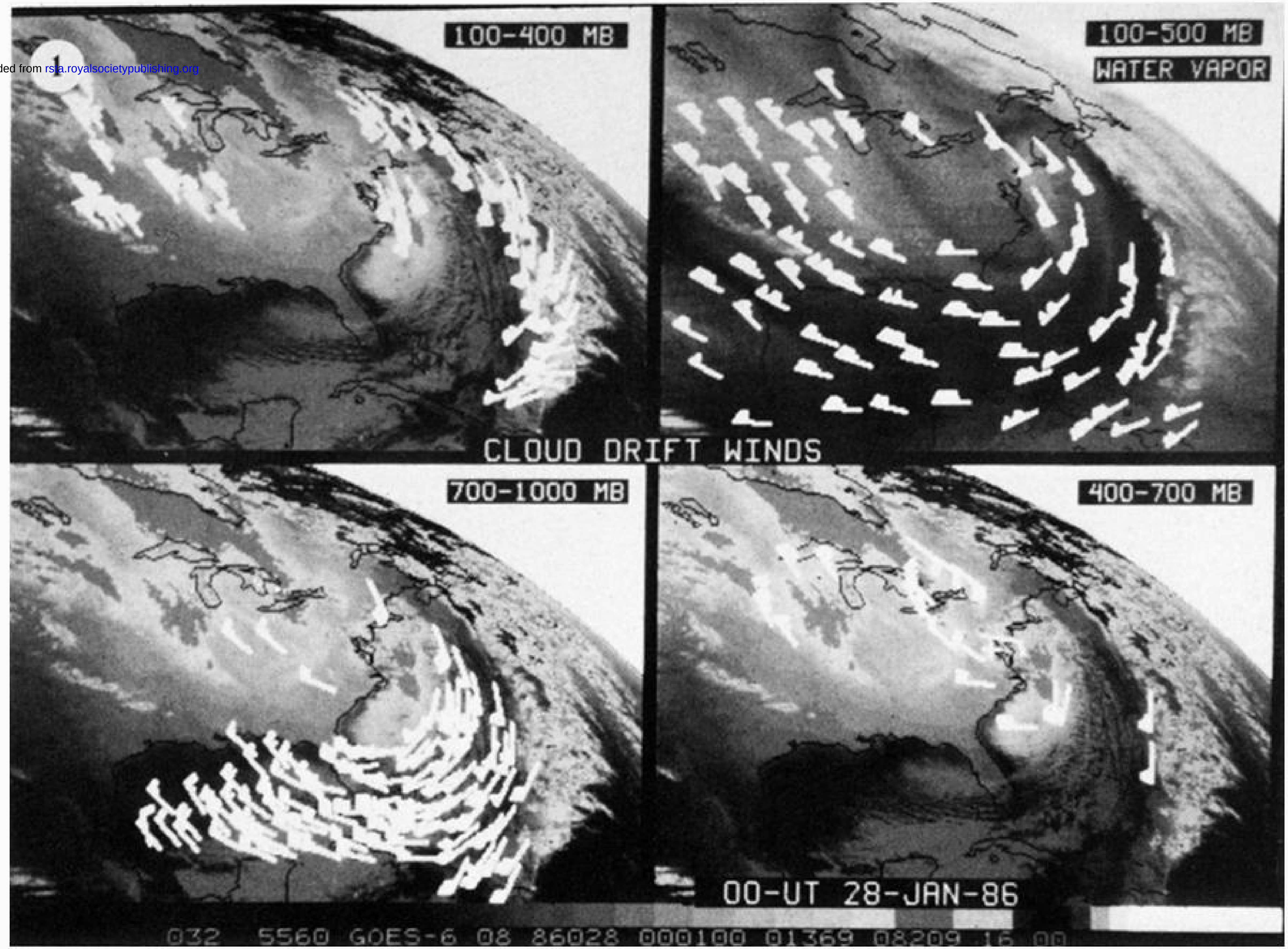


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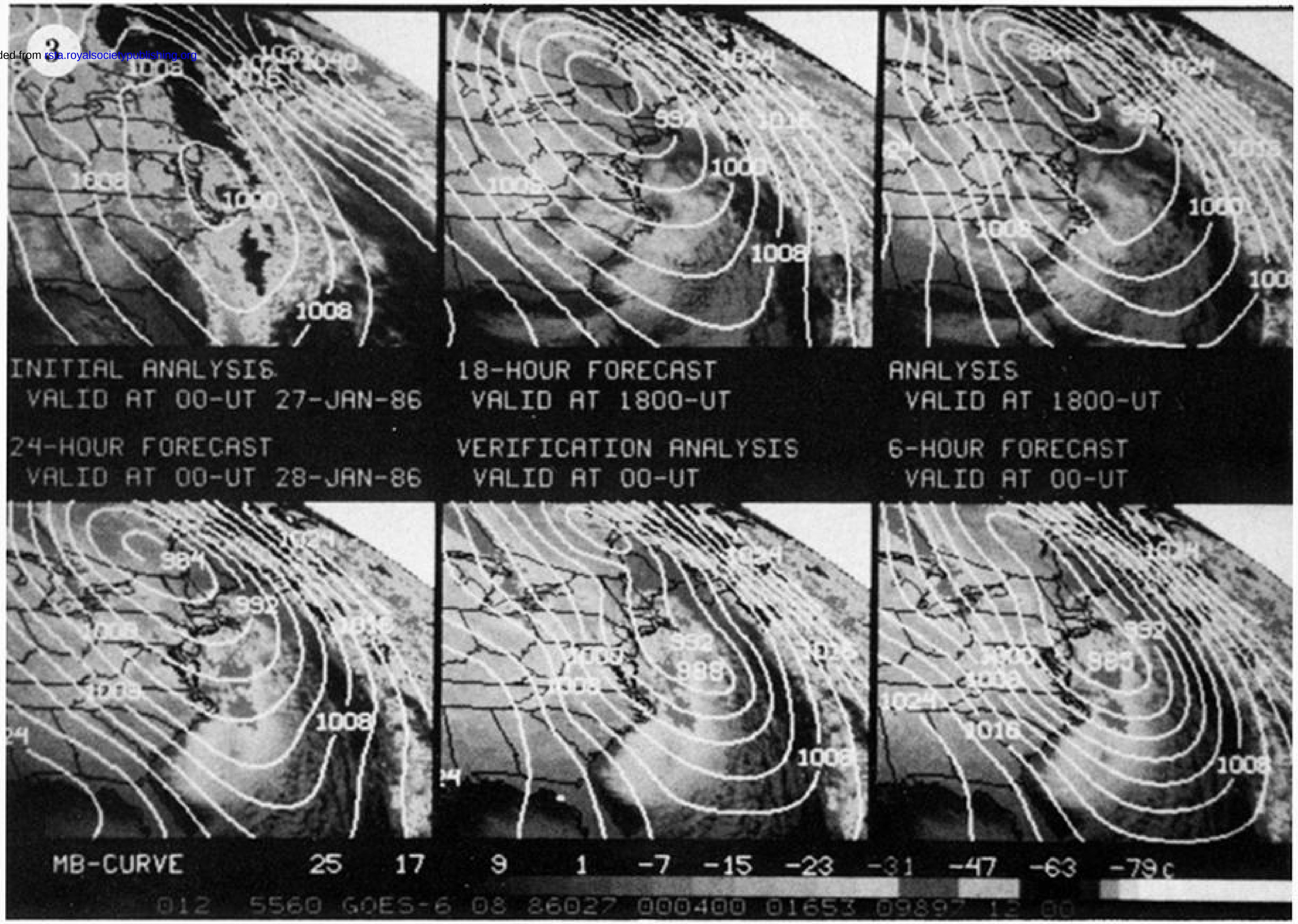


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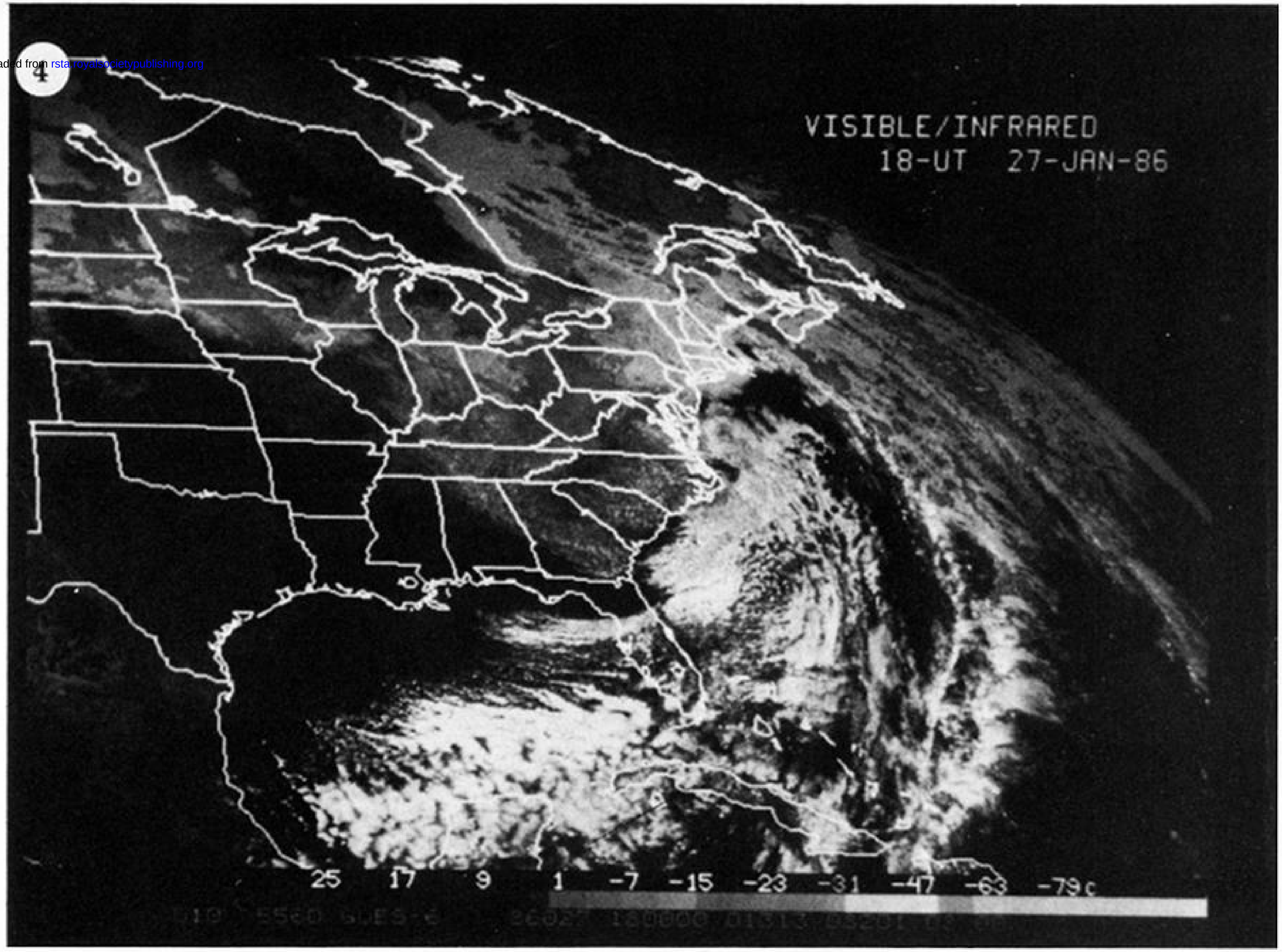


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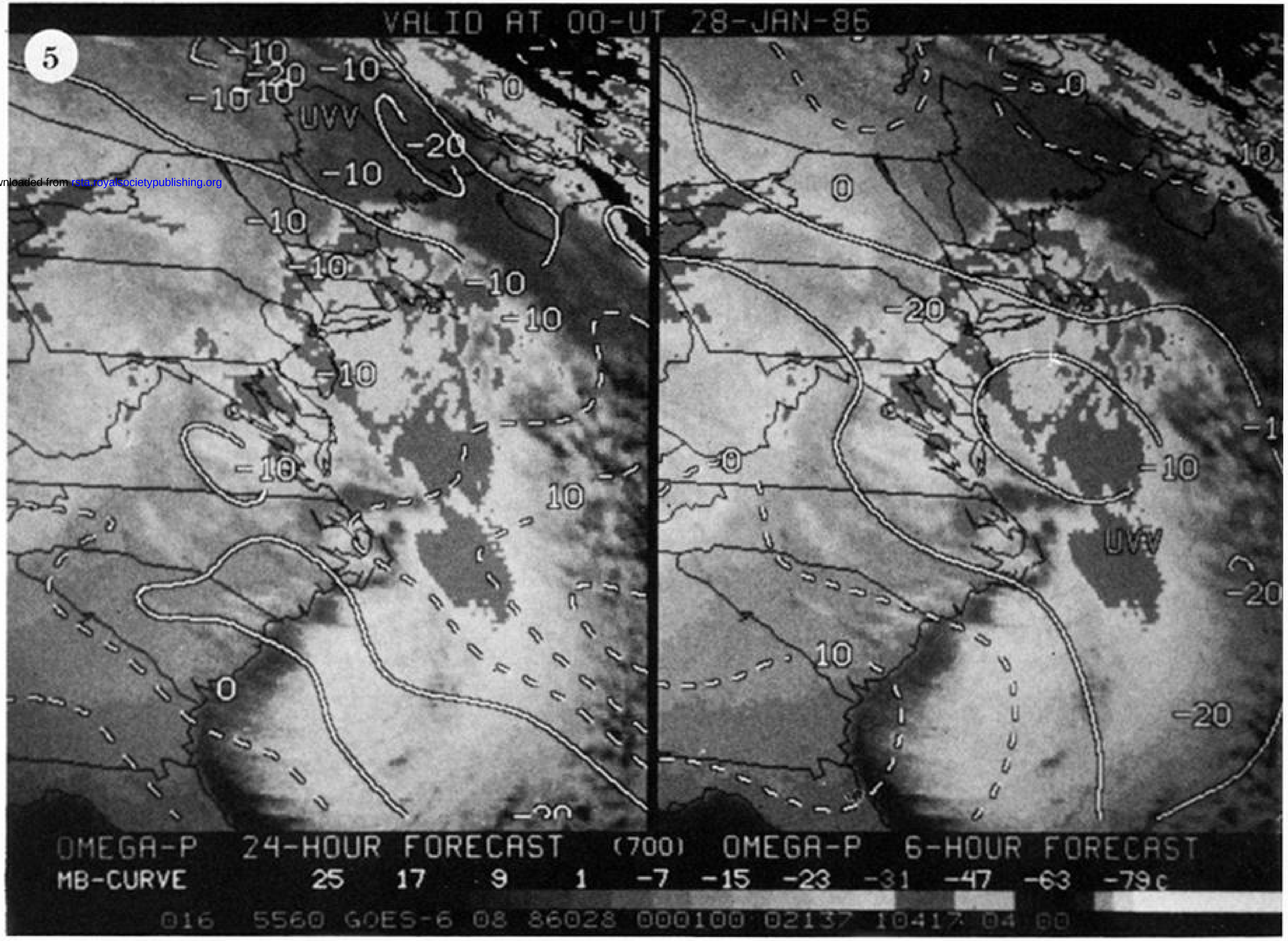


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