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"The UB/NMC Model & Results in the Tropics"

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Introduction

During the AMEX (Australian Monsoon Experiment), 10 January through 15 February 1987, four tropical cyclones, *Connie, Irma, Damien* and *Jason*, developed in the north and north-west Australian region (Manchur 1987, Heckley and Puri 1988). Cyclone *Irma* developed simultaneously with cyclone *Connie* (forecast period in this study: 18 - 20 January 1987). However, their growth was due to very different conditions. *Connie* formed north-east of Derby and moved southwest steered by an upper-level anticyclonic circulation. *Irma* evolved from an area of deep convection in the northern Gulf of Carpentaria. *Damien* formed from a monsoonal low that developed off the Kimberley coast, to the north of Cape Leveque (forecast period: 02 - 04 February 1987). *Jason* developed from a tropical low within a cloud mass over northern Cape York Penisula and the Gulf of Carpentaria (forecast period: 11 - 13 February 1987).

The UB/NMC (University of Belgrade/National Meteorological Center, Washington) eta model was used to predict the AMEX tropical cyclones listed above. The eta model is being run experimentally at University of Belgrade and quasi-operationally at the NMC for extratropical integrations. This is the first model integration in the tropics.

Davidson (1989) successfully simulated AMEX tropical cyclone *Irma* using FSU (Florida State University) regional prediction model and operational ECMWF analyses without and with additional AMEX data. He reported the capability of the model to realistically simulate genesis and sensitivities of the simulation to the internal and boundary conditions.

Model summary

The general characteristics of the UB/NMC eta model are the following:

- limited area and grid point model;
- defined on semi-staggered Arakawa E grid (Arakawa and Lamb 1977);
- uses a special technique to prevent grid separation (Mesinger 1973; Janjić 1974, 1979);
- vertical coordinate is the step-mountain, η coordinate, as a generalization of the σ coordinate (Phillips 1957), with the step-like representation of mountains (Mesinger 1984, Mesinger *et al.* 1988), defined by

$$\eta = \frac{p - p_T}{p_S - p_T} \eta_S , \qquad (1)$$

where

$$\eta_S = \frac{p_{rf}(z_S) - p_T}{p_{rf}(0) - p_T} . \qquad (2)$$

Here p is pressure, and subscripts T and S denote the values at the top of the model atmosphere and at the Earth's surface, respectively; z is geometric height, and $p_{rf}(z)$ is a suitably defined reference pressure as a function of z. Specifically, here we have chosen

$$p_{rf}(z) = p_{rf}(0) \exp(-\Gamma z/RT),$$

where $p_{rf}(0)=1013.25$ mb, $T=288$K, $\Gamma=6.50°/1000$m, $R=287.04$ $\mathrm{Jkg^{-1}K^{-1}}$. The surface heights z_S are allowed to take only a discrete set of values, chosen so that mountains are constructed from the three-dimensional grid boxes (Mesinger and Janjić 1985).

A schematic representation of mountains using so defined "step-mountain" coordinate is shown in Fig. 1. u, T and p_S are grid points in which the u component of velocity, temperature, and surface pressure are represented, respectively. Variables u, v, T, and specific humidity, are defined in the middle of the layers. Turbulent kinetic energy is defined at layers interfaces. In contrast to the sigma coordinate, the surfaces of the eta coordinate are quasi-horizontal. Thus, the steep slopes of the coordinate surfaces are eliminated, together with their undesirable effects in the sigma system (pressure gradient force error, advection and lateral diffusion problems).

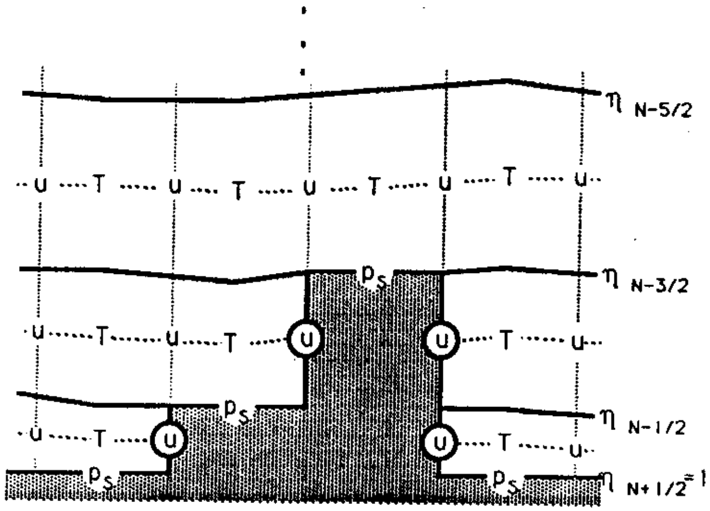

Fig. 1 Schematic representation of the step-mountain η coordinate (After Mesinger *et al.* 1988).

- built-in nonlinear energy cascade control in horizontal advection (Janjić 1984);
- split-explicit time differencing (Mesinger 1974, 1977; Janjić 1979);
- the Mellor-Yamada Level 2.5 scheme for planetary boundary layer (Vager and Zilitinkevitch 1968; Zilitinkevitch 1970; Mellor and Yamada 1974, 1982);
- the Mellor-Yamada Level 2 scheme for the "surface" layer (Mellor and Yamada 1974, 1982), with a shallow dynamical turbulence layer at the bottom;
- fourth order lateral diffusion scheme with the diffusion coefficient depending on deformation and the turbulent kinetic energy;
- surface processes: Ground surface processes which cause changes of temperature and wetness, and include surface hydrology, are designed following Miyakoda and Sirutis (1977, 1984) (Janjić 1989);
- large scale precipitation and modified Betts and Miller shallow and deep convection schemes (Betts 1986; Betts and Miller 1986):

Condensation occurs if relative humidity is greater then the given threshold (95%). Condensed water from higher levels evaporates in lower layers if relative humidity is less then 95%. The remaining condensed water is considered as large scale precipitation.

Shallow convection is employed if "clouds" extend over 2-4 layers; if clouds extend through 5 and more layers deep convection is used however only if adjustment towards reference temperature and moisture profiles in the scheme results in positive precipitation. For the reference moisture profiles, deficits of saturation pressure at: cloud bottom (-30 mb), freezing level (-50 mb), and cloud top (-20 mb), are used.

- the NMC version of the GLAS (Goddard Laboratory for Atmospheric Sciences) radiation scheme with interactive random overlap clouds (Davies 1982; Harshvardhan and Corsetti 1984).

Tropical cyclones description

Only synoptic aspects important for the forecast experiments described here are summarized below.

Connie formed at 15.8°S, 124.8°E, northeast of Derby, at 0000 UTC 15 January 1987 (Manchur 1987). It moved southwest steered by an upper-level high pressure system located over central Australia, and continued to intensify. Central surface pressure at 0000 UTC 18 January 1987 (initial data in this study) was 988 mb, at 0000 UTC 19 January 1987 it was 962 mb and at 0000 UTC 20 January 1987 it was 974 mb. *Connie* dissipated at 36.9°S, 127.1°E at 0600 UTC 23 January 1987.

Irma developed from an area of deep convection in the northern Gulf of Carpentaria at 0000 UTC 19 January 1987, with central surface pressure of 998 mb (Manchur 1987). *Irma* moved in a west-southwesterly direction across the Gulf of Carpentaria, with central surface pressure of 985 mb at 0000 UTC 20 January 1987. The system lost its identity at 0000 UTC 21 January 1987 in the central Northern Territory. *Irma* became a very active rain depression with a 24-hour total rainfall of 409 mm at Larrimah.

Damien formed from a monsoonal low that developed off the Kimberley coast, to the north of Cape Leveque, on 31 January 1987. It moved generally southwest (parallel to the coast) steered by an upper-level high pressure system located over central Australia. Central surface pressure at 0000 UTC 02 February 1987 (initial data) was 988 mb (15.5°S, 123.3°E), at 0000 UTC 03 February 1987 it was 980 mb (maximum intensity) and at 0000 UTC 04 February 1987 it was 983 mb (Manchur 1987). *Damien* dissipated at 20.0°S, 111.0°E at 0000 UTC 09 February 1987.

Jason developed from a tropical low within a cloud mass over northern Cape York Peninsula and the northeastern Gulf of Carpentaria about 06 February 1987. Firstly it moved west-southwest across Gulf of Carpentaria, then it reached cyclonic intensity and after coastal crossing it turned and moved southward over water by 0000 UTC 11 February 1987 (initial data) with central surface pressure of 994 mb. Central surface pressure at 0000 UTC 12 February 1987 was 980 mb, at 0000 UTC 13 February 1987 it reached a maximum intensity of 970 mb (15.1°S, 139.6°E) (Manchur 1987).

Model orography, initial and boundary conditions

The model horizontal domain was defined between 00° to 30°S and 105°E to 155°E.

For the above region, the U.S. NAVY high resolution (10'×10') orography dataset, provided by NCAR, was used to compute "silhouette" mountains (Mesinger *et al.* 1988). Heights of the model step-mountains were obtained by averaging over group of four neighboring points and were subsequently rounded-off to the nearest reference interface elevation.

The model orography for the above region is shown in Fig. 2.

The initial data used for model integrations were from 0000 UTC 18 January 1987 for *Connie* and *Irma*, from 0000 UTC 02 February 1987 for *Damien*, and from 0000 UTC 11 February 1987 for *Jason*

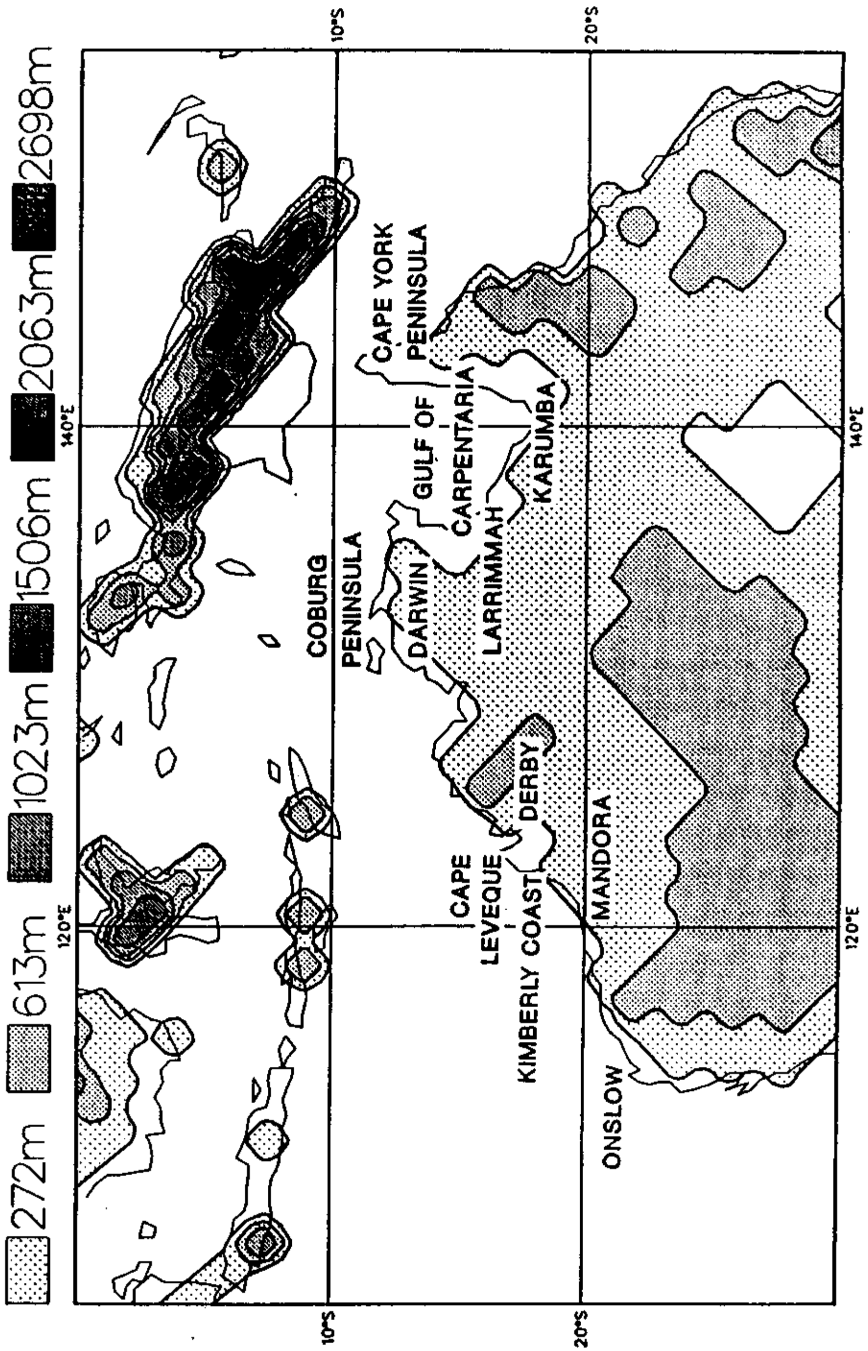

Fig. 2 Step-mountains used in the model.

Model initial fields of geopotential height, wind components and specific humidity were defined on ten standard pressure levels (1000, 850, 700, 500, 400, 300, 250, 200, 150 and 100 mb). These fields were calculated by bilinear interpolation from ECMWF global initialized analyses to 0.5°×0.5° transformed longitude/latitude E grid. Sea-surface temperature was also obtained from ECMWF global field by bilinear interpolation. Albedo and ground wetness were taken from ECMWF climate data.

The initial anlyses of geopotential height, streamlines and isotachs at 200,500 and 850 mb and sea-level pressure are shown in Figs. 3 to 5.

Interpolation of geopotential height and specific humidity from pressure levels to eta surfaces is done quadratically in ln(p). However, wind components in the middle of eta layers are obtained by linear interpolation in ln(p). Initial temperature in the middle of eta layers was calculated, from the given geopotential height and relative humidity, by the hydrostatic equation.

Time-dependent boundaries for all variables were updated by linear time interpolation from ECMWF forecast every 6 hours of integration.

Forecasts

The model forecasts are verified at T+48 hours against ECMWF initialized analyses.

The 48-hour forecast with corresponding verification is shown in Figs. 6 and 7. High pressure over central and northern Australia at 200 mb and development of cyclones at upper levels (500 and 850 mb) are successfully predicted. Verifying analysis and the forecast of the wind field are in reasonable agreement. Positions of cyclones agree very

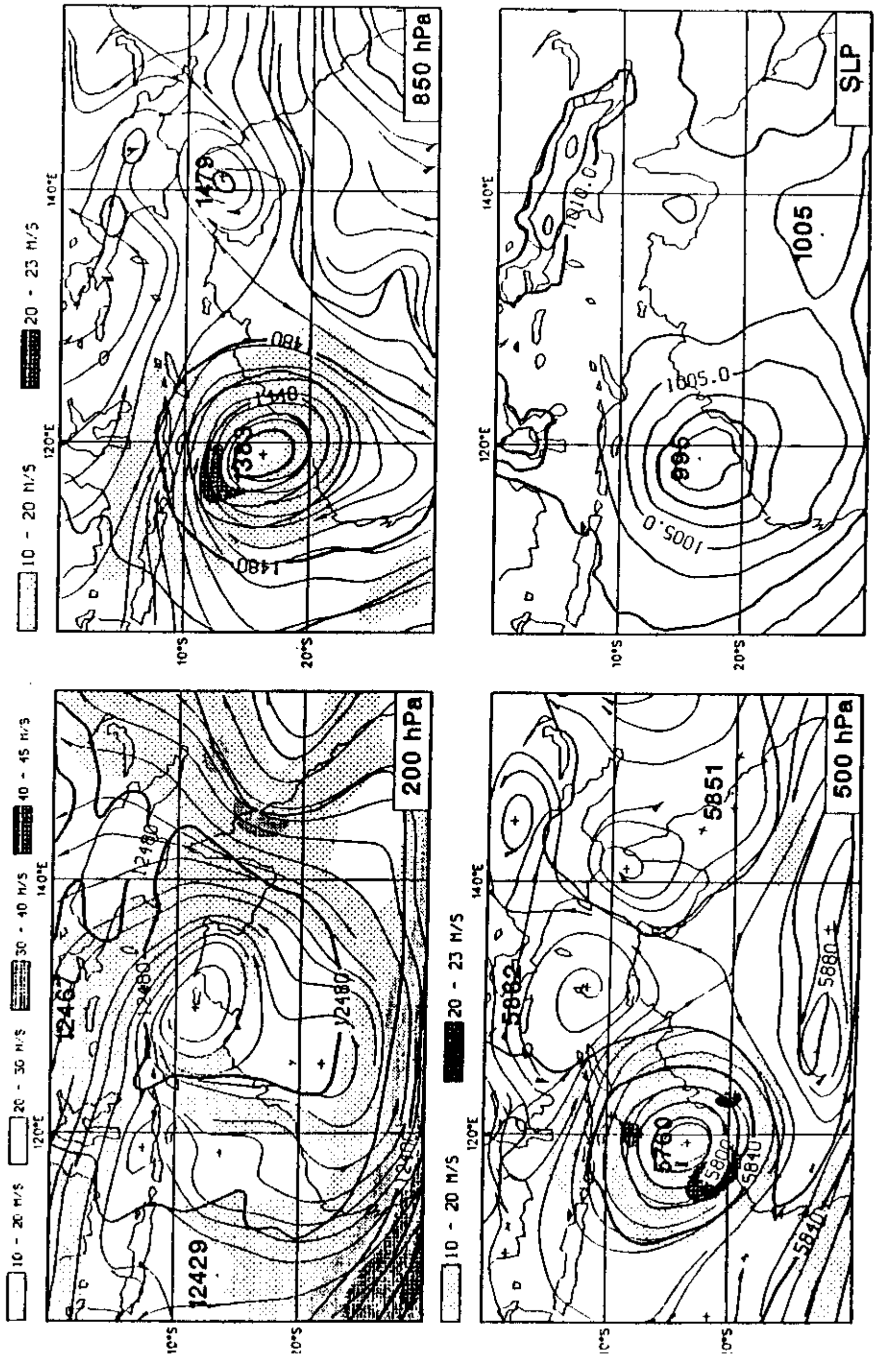

Fig. 3 Initial conditions - *Connie* and *Irma*: Analyses of geopotential height (200 mb - contour interval is 40 m, 500 mb - 20 m, 850 mb - 20 m), streamlines, isotachs (shown by shading, contour interval is 10 m/s) and sea-level pressure (contour interval is 2.5 mb) at 0000 UTC 18 January 1987.

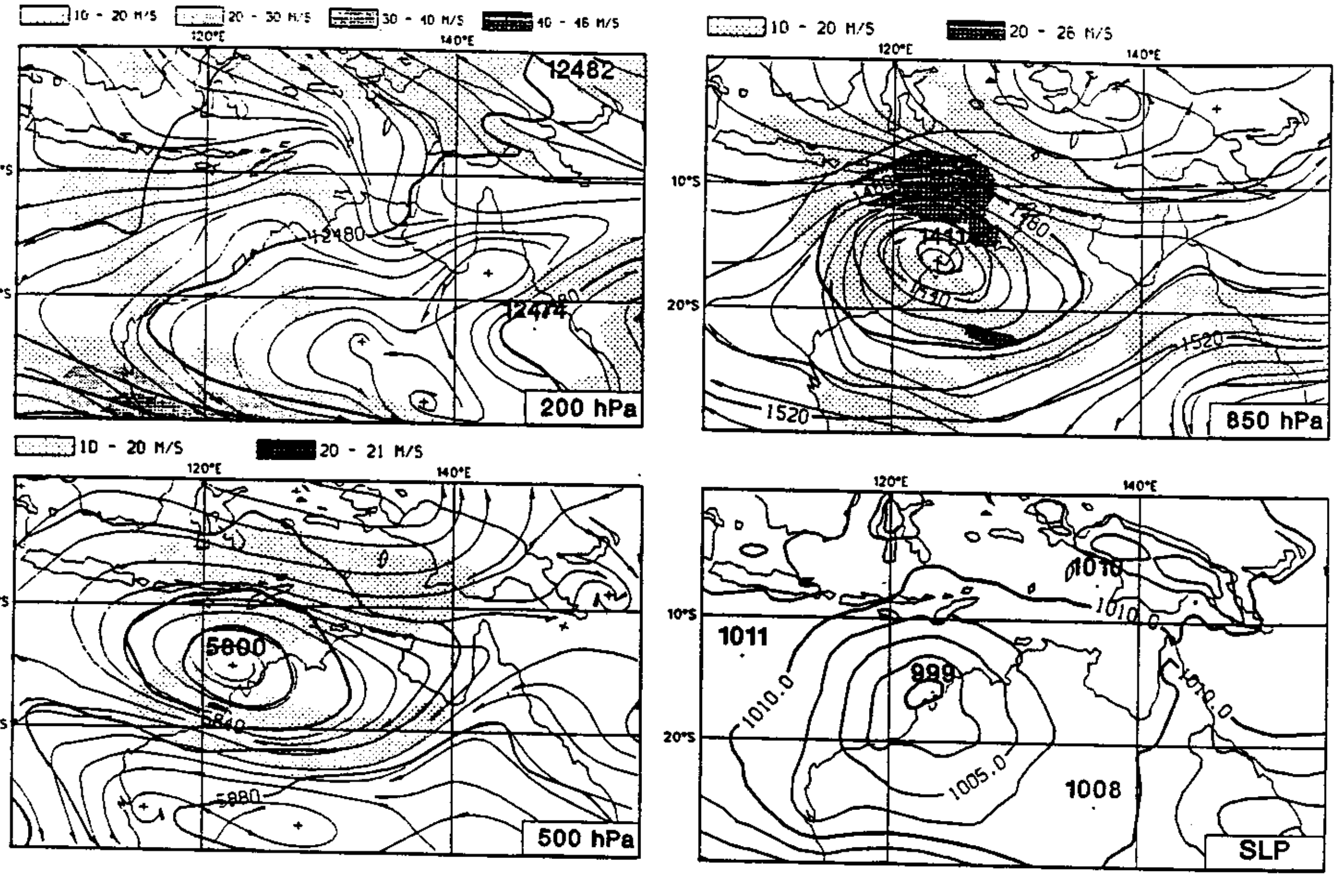

Fig. 4 Initial conditions - *Damien*: as in Fig. 3, but at 0000 UTC 02 February 1987.

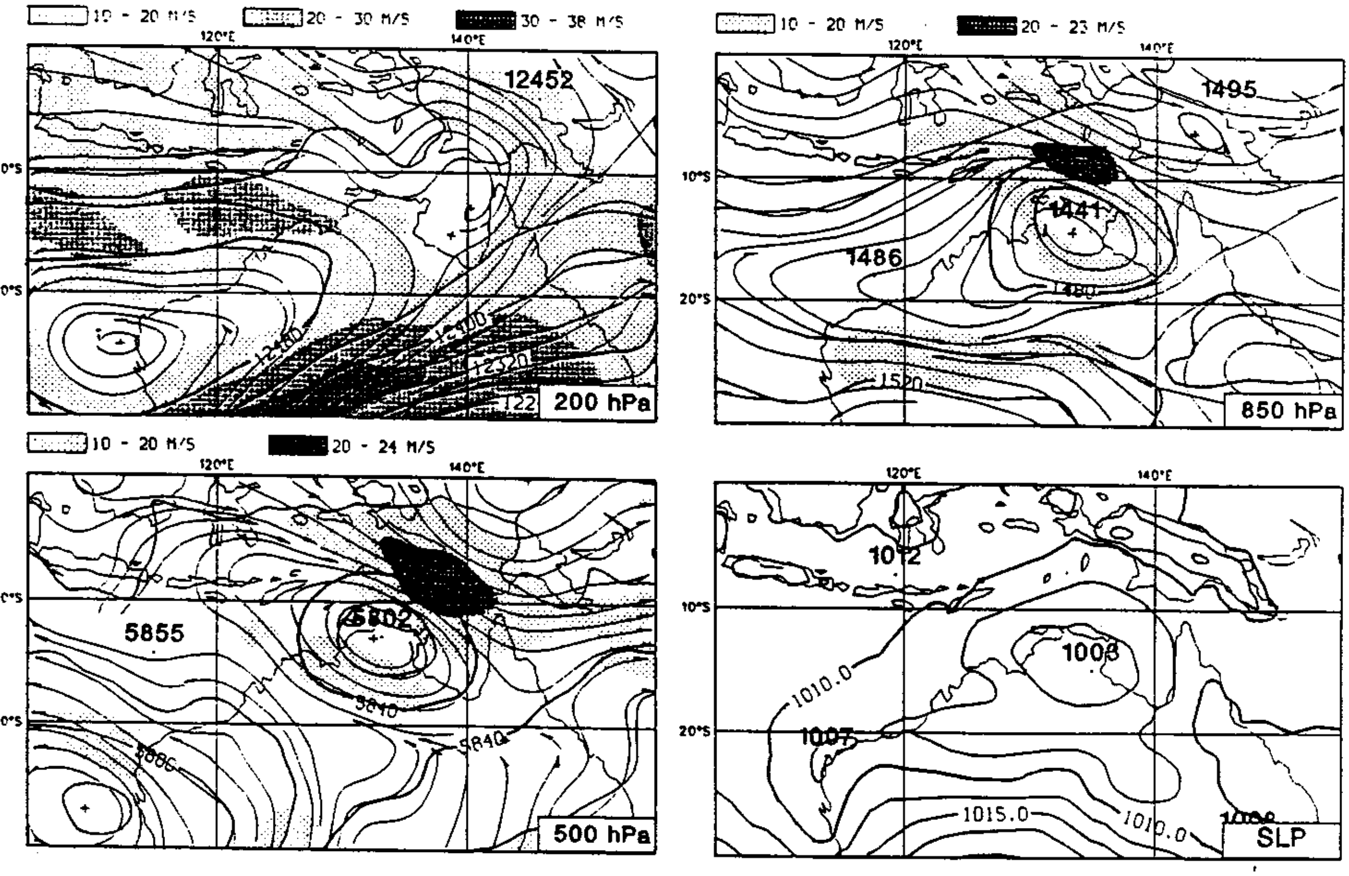

Fig. 5 Initial conditions - *Jason*: as in Fig. 3, but at 0000 UTC 11 February 1987.

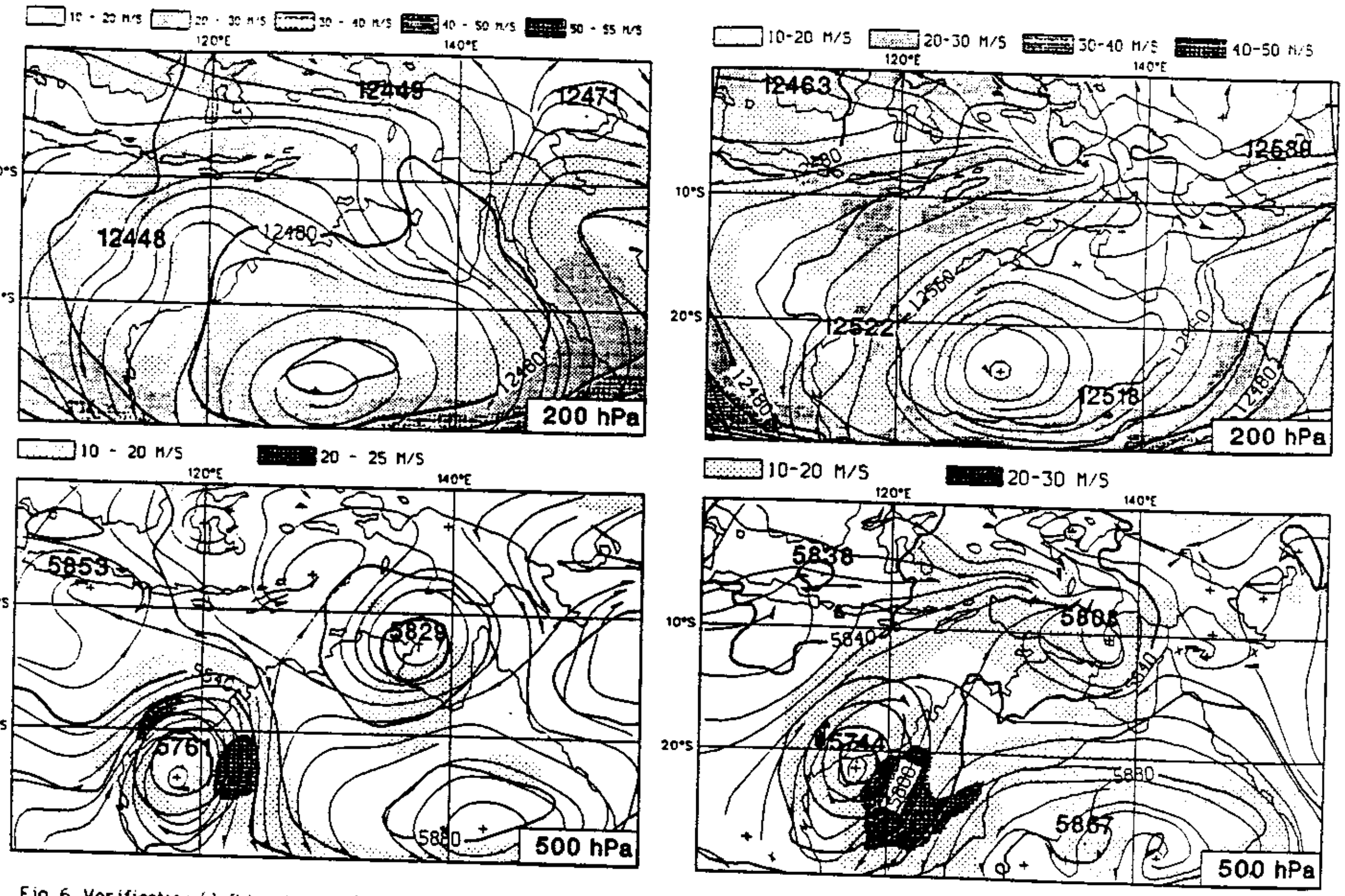

Fig. 6 Verification (left hand panels) and 48-hour forecast (right hand panels) of *Connie* and *Irma*: 200 mb and 500 mb; as in Fig. 3.

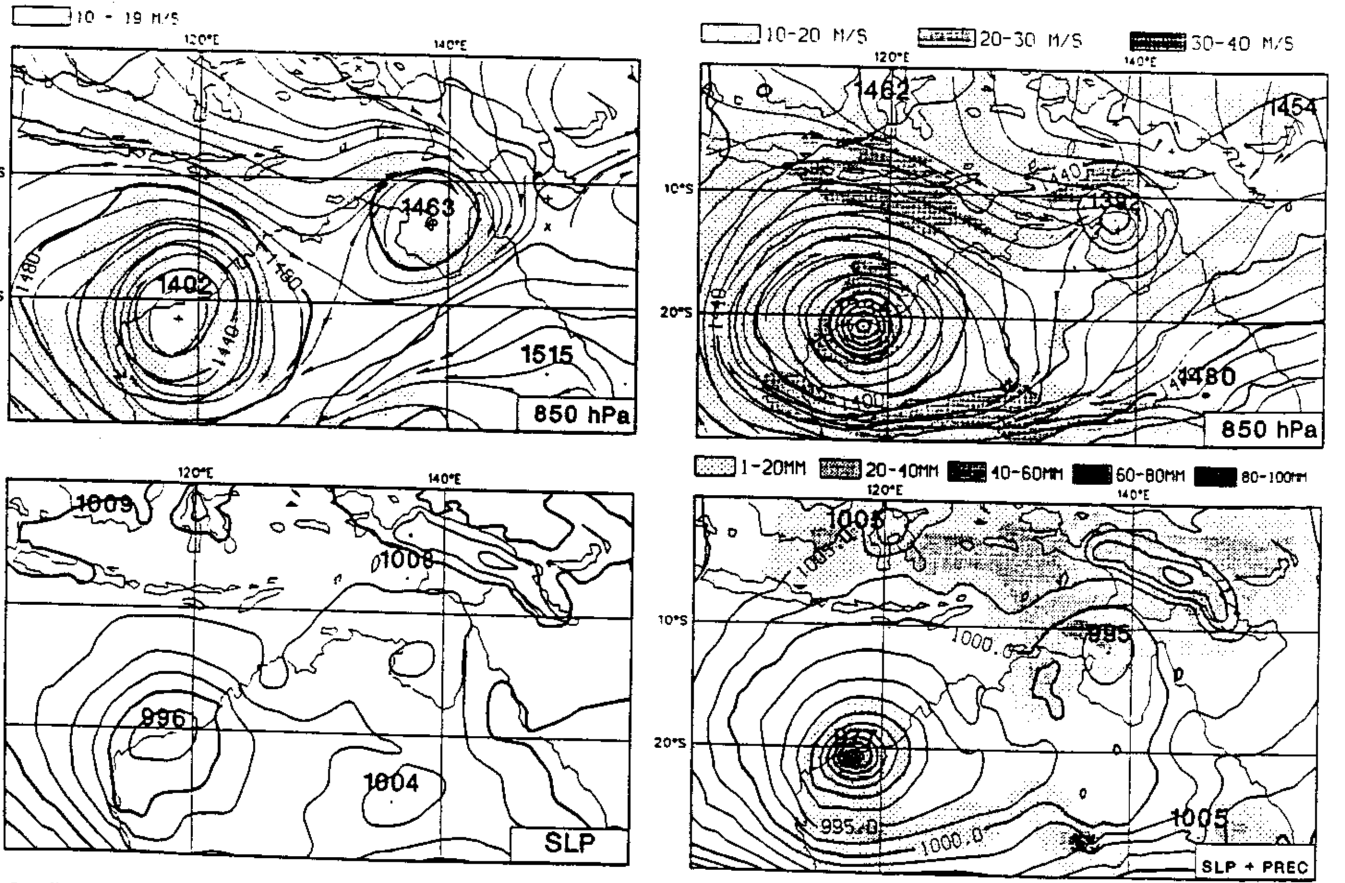

Fig 7 Verification (left hand panels) and 48-hour forecast (right hand panels) of *Connie* and *Irma*: 850 mb, sea level pressure (as in Fig. 3) and total precipitation (shown by shading) accumulated over last 12 hours of forecast (contour interval 20 mm).

closely. Central pressure of 977 mb and 995 mb in *Connie* and *Irma*, respectively, is predicted, while in observations (Manchur 1987) these values are 974 mb and 985 mb. The model correctly predicted the development of a surface circulation of *Irma*.

Tracks of predicted, observed and analysed central pressure of *Connie* and *Irma* are shown in Figs. 8 and 9. It can be seen that model has predicted tracks reasonably well. The 48-hour forecast track errors are smaller than initialized analysis track errors compared with the observed track, although the initial cyclone position errors in analyses are large. The 48-hour forecast central sea level pressure errors are smaller than the same errors in the analyses compared with the observations.

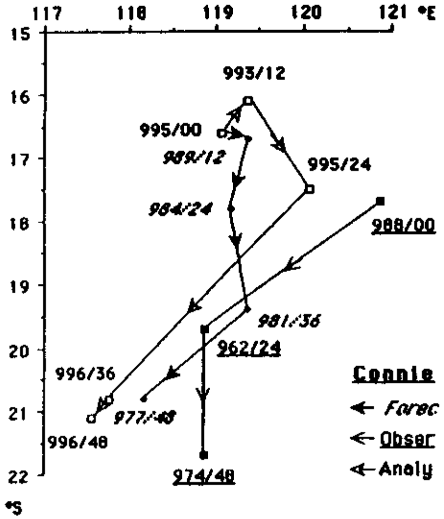

Fig. 8 Tracks of predicted, observed and analysed central pressure of *Connie*

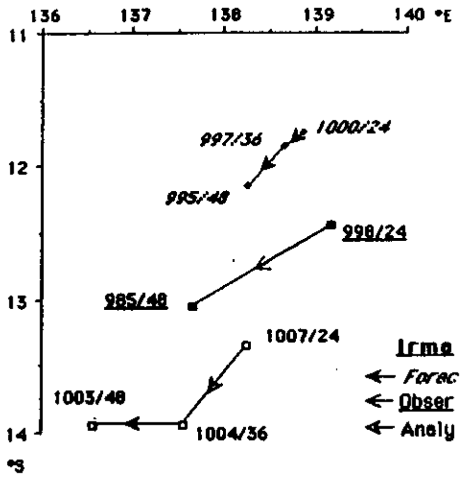

Fig. 9 Tracks of predicted, observed and analysed central pressure of *Irma*.

The 48-hour forecast with corresponding verification (only 850 mb and sea level pressure maps) of tropical cyclone *Damien* is shown in Fig. 10. There is a good agreement between forecast and verification. Tracks of *Damien* with surface pressure are shown in Fig. 11. There is reasonable agreement between tracks.

Forecast of tropical cyclone *Jason* with corresponding verification is shown at Fig. 12. There is a good agreement of predicted cyclone positions against initialized analyses, but central pressure is better predicted than analysed. Tracks of *Jason*, with surface pressure are shown in Fig. 13. There is a difference in initial position in observation and analysis, although after 24 hours tracks are well comparable.

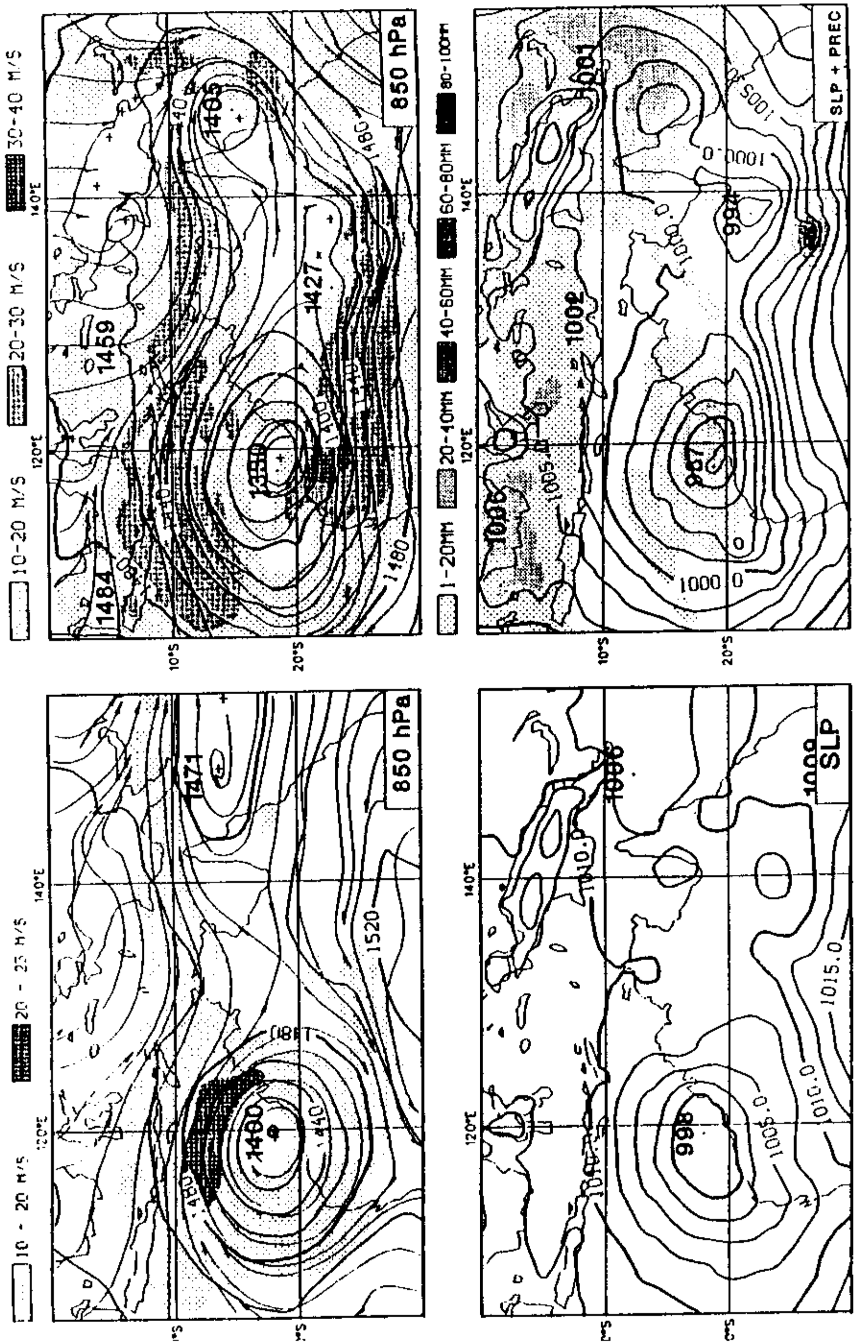

Fig. 10 Verification and 48-hour forecast of *Damien*: 850 mb, sea level pressure and total precipitation; as in Fig.7.

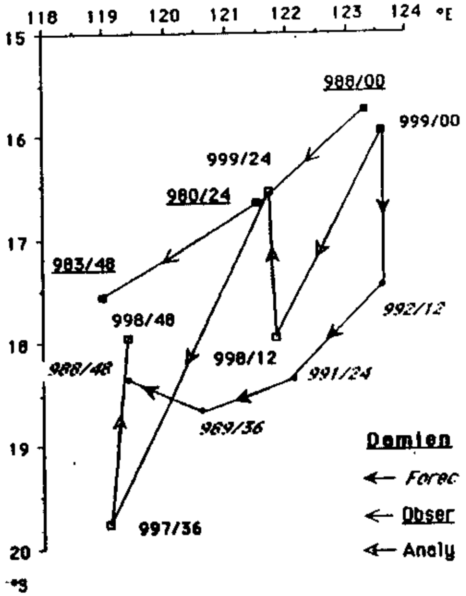

Fig. 11 Tracks of predicted, observed and analysed central pressure of *Damien*.

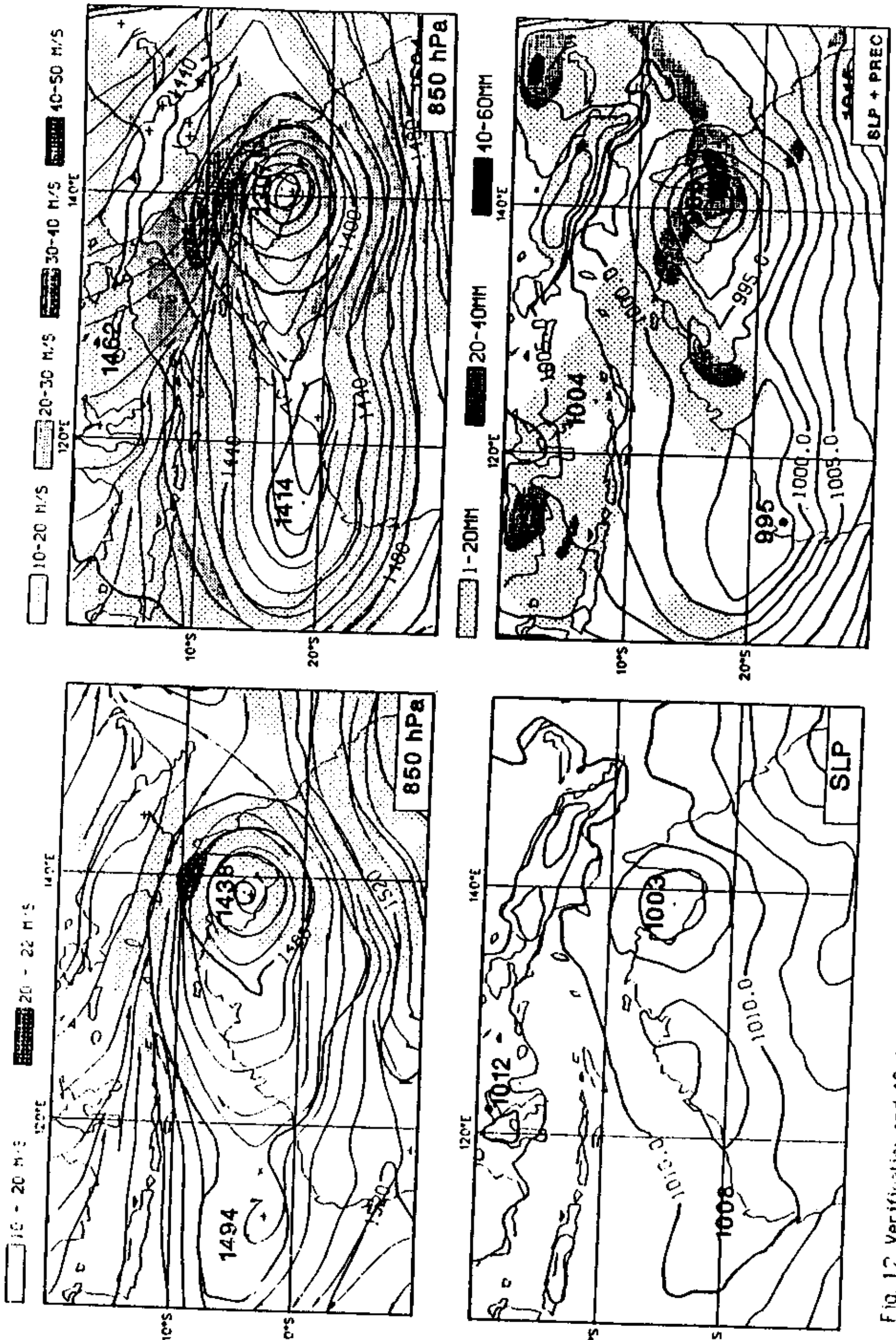

Fig. 12 Verification and 48-hour forecast of *Jason*: 850 mb, sea level pressure and total precipitation; as in Fig. 7.

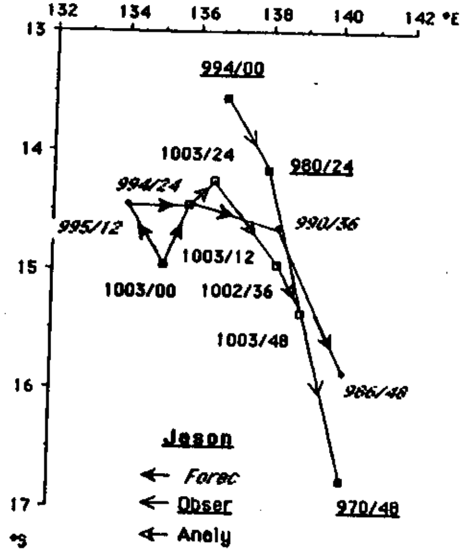

Fig. 13 Tracks of predicted, observed and analysed central pressure of *Jason*.

Model sensitivity

Some model's sensitivities are summarized and discussed in the case of tropical cyclone *Connie*.

The sensitivity to the initial (IC) and boundary conditions (BC): The control forecast is based on the ECMWF operational initialized analyses and forecasts for IC and BC, respectively. There is a small sensitivity to the unitialised analyses as IC. The sensitivities from the boundaries are small too, using initialized analyses as BC.

The sensitivity to the surface fluxes: A large impact can be seen from the surface heat and moisture fluxes in Fig. 14.

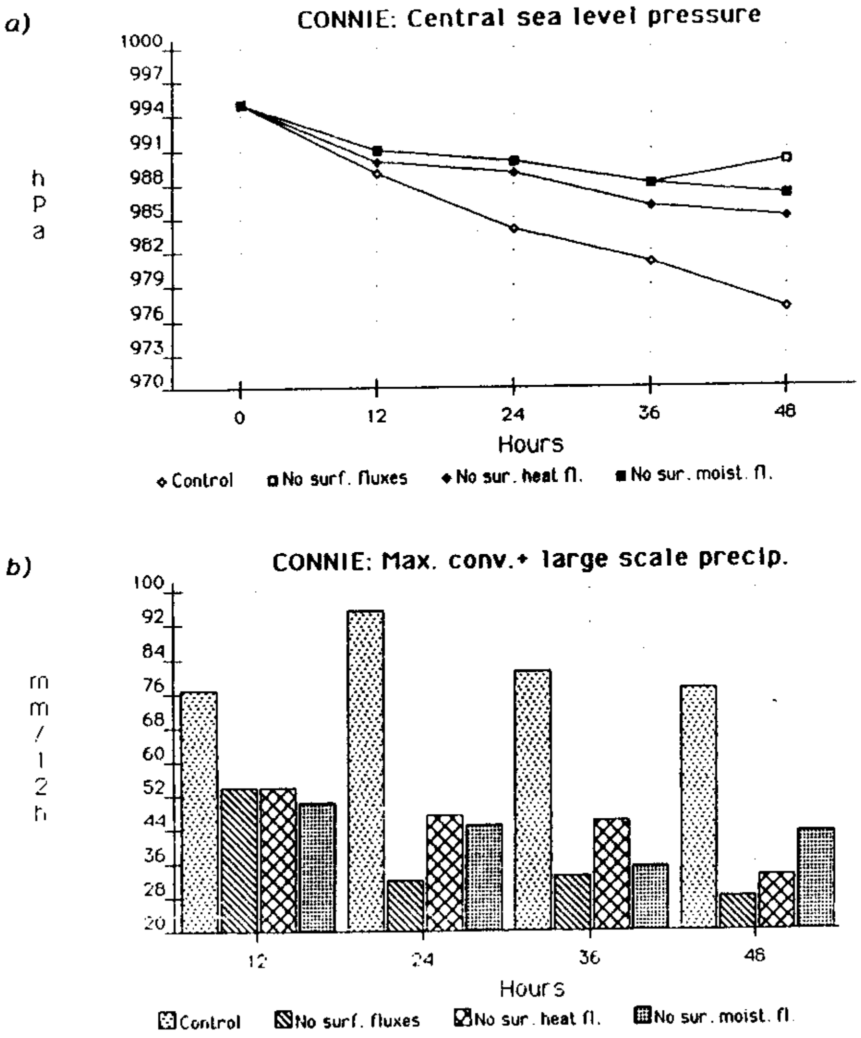

Fig. 14 The central sea level pressure (a) and precipitation (b) of *Connie* during 48-hour integration with and without surface fluxes.

The sensitivity to the SST: The most important parameter of the tropical cyclone genesis, intensity and motion is the SST. The SST is about 28°C in the control experiment in the *Connie* region. The sensitivity to the SST variations form 26°C to 30°C in step of 1° is shown in Fig. 15.

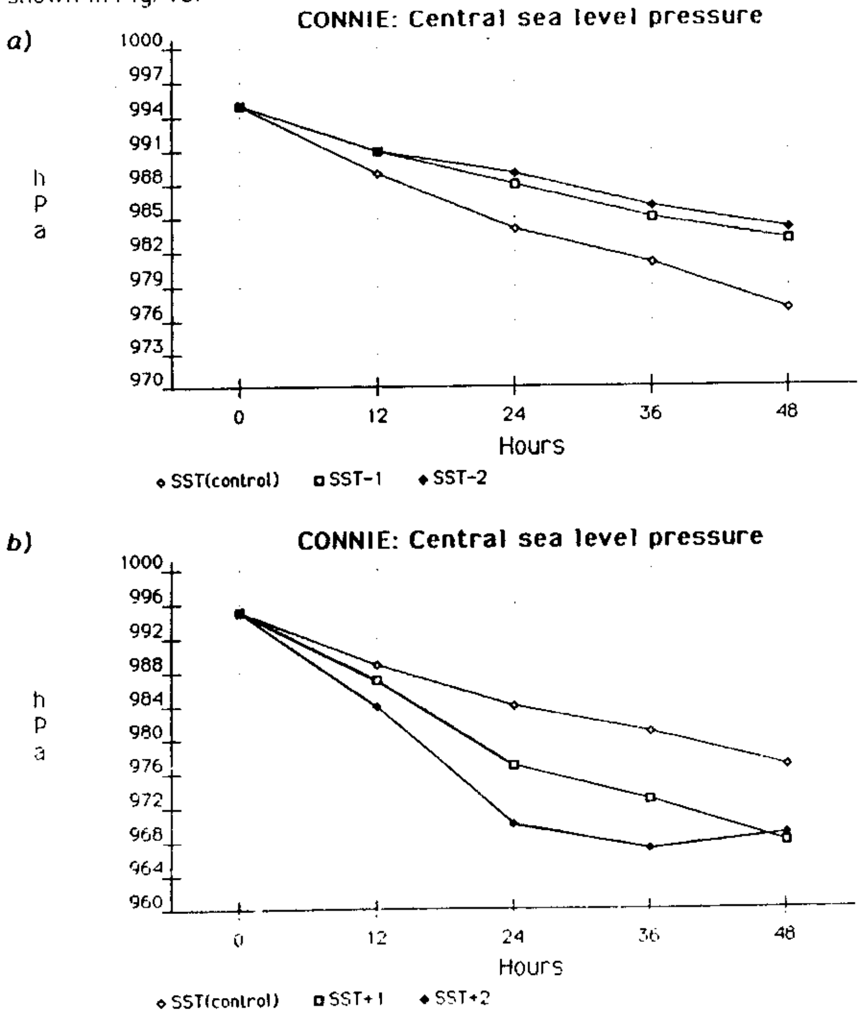

Fig. 15. The central sea level pressure of *Connie* during 48-hour integration with different SST (a: SST-2, SST-1, b: SST+1, SST+2)

The sensitivity to the Betts-Miller convective parameterization:

The shallow (non-precipitating) convection is performed for the clouds 2-4 layers deep, and the deep convection for those extending 5 and more layers, but only if the adjustment towards the reference temperature and moisture profiles results in the positive precipitation. The reference moisture profile is prescribed by the deficits of the saturation pressure (DSP) at cloud bottom (-30 mb), freezing level (-50 mb) and cloud top (-20 mb). The model sensitivity to the different DSP is shown in Fig. 16.

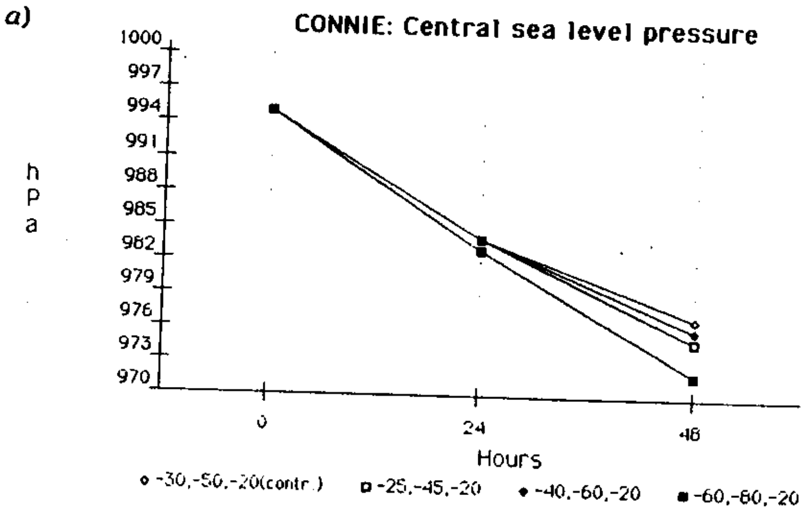

Fig. 16. The central sea level pressure (a) and precipitation (b) of *Connie* during 48-hour integration with different DSP in Betts-Miller convective parameterization.

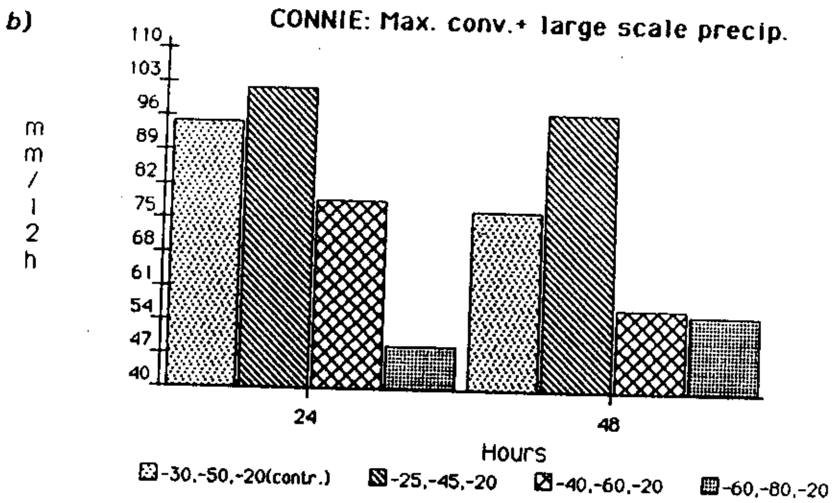

Fig. 16. (Cont.)

Conclusion

It was demonstrated that the UB/NMC eta model predicted correctly most of the features of tropical cyclones. Timing of cyclogenesis and subsequent cyclone tracks, central surface pressure, winds (especially maximum winds) and precipitation were predicted with reasonable skill. However, it can be seen that positions and central surface pressure of cyclones in analyses and observations, especially in initial conditions of *Connie* and *Jason*, are different.

Acknowledgments

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Figure captions

Fig. 1 Schematic representation of the step-mountain η coordinate (After Mesinger *et al.* 1988).

Fig. 2 Step-mountains used in the model.

Fig. 3 Initial conditions - *Connie* and *Irma*: Analyses of geopotential height (200 mb - contour interval is 40 m, 500 mb - 20 m, 850 mb - 20 m), streamlines, isotachs (shown by shading, contour interval is 10 m/s) and sea-level pressure (contour interval is 2.5 mb) at 0000 UTC 18 January 1987.

Fig. 4 Initial conditions - *Damien*: as in Fig. 3, but at 0000 UTC 02 February 1987.

Fig. 5 Initial conditions - *Jason*: as in Fig. 3, but at 0000 UTC 11 February 1987.

Fig. 6 Verification (left hand panels) and 48-hour forecast (right hand panels) of *Connie* and *Irma*: 200 mb and 500 mb; as in Fig. 3.

Fig. 7 Verification (left hand panels) and 48-hour forecast (right hand panels) of *Connie* and *Irma*: 850 mb, sea level pressure (as in Fig. 3) and total precipitation (shown by shading) accumulated over last 12 hours of forecast (contour interval 15 mm).

Fig. 8 Tracks of predicted, observed and analysed central pressure of *Connie*.

Fig. 9 Tracks of predicted, observed and analysed central pressure of *Irma*.

Fig. 10 Verification and 48-hour forecast of *Damien*: 850 mb, sea level pressure and total precipitation; as in Fig. 7.

Fig. 11 Tracks of predicted, observed and analysed central pressure of *Damien*.

Fig. 12 Verification and 48-hour forecast of *Jason*: 850 mb, sea level pressure and total precipitation; as in Fig. 7.

Fig. 13 Tracks of predicted, observed and analysed central pressure of *Jason*

Fig. 14 The central sea level pressure (a) and precipitation (b) of *Connie* during 48-hour integration with and without surface fluxes.

Fig. 15 The central sea level pressure of *Connie* during 48-hour integration with different SST (a: SST-2, SST-1; b: SST+1, SST+2).

Fig. 16 The central sea level pressure (a) and precipitation (b) of *Connie* during 48-hour integration with different DSP in Betts-Miller convective parameterization.