Impact of boundary-layer parameterization in simulating the marine boundary layer for INDOEX

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The impact of two boundary layer parameterization schemes on the prediction of Indian monsoon systems by a global spectral model has been seen. The non-local closure scheme shows a positive impact on the prediction of some important synoptic features, including tracking of monsoon depressions, and precipitation and systematic errors of the model. The scheme is used to study certain features of the marine boundary layer structure over the INDOEX region.

THE parameterization of the planetary boundary layer (PBL) in the global spectral models remains one of the most important aspects since frictional convergence and divergence taking place within the PBL has a significant impact on the type of weather occurring at any place in the world. Air masses are modified considerably through exchange processes within the PBL. Atmospheric water vapour, which is the carrier of large amounts of heat energy in the free atmosphere, has its source at the earth–air interface. The rate at which the water vapour is injected into the free atmosphere depends upon the properties of the PBL. Over the tropics, significant diurnal variations in wind speed, static stability, turbulent exchange and convective activity occur. Hence, steady state models are not appropriate for the tropical PBL, and this is particularly true over the vast oceanic regions, especially over the Arabian Sea, that exhibit the characteristic trade wind inversion with varying degrees of stability and intensity. It is necessary that the PBL over the tropics, as is the case in the extra tropics, should be represented as realistically as possible in numerical models. In global models, the large-scale atmospheric flow determines to a significant extent the properties of the PBL, and the PBL in turn reacts to these external forcings and modifies the large-scale flow.

In India, the National Centre for Medium Range Weather Forecasting (NCMRWF) was established, in part, to develop an appropriate medium range analysis forecast system (MAFS) for the monsoon region and provide agrometeorological advisory services for the farming community on an operational basis. The global model at NCMRWF is adopted from the National Centers for Environmental Prediction, previously known as the National Meteorological Center, USA. The global data assimilation scheme involves spectral statistical interpolation, and six-hour forecasts of the global model provide the first guess for the subsequent analysis. Five-day forecasts are obtained in real time based on the analysis at 0000 GMT. Details of the global spectral model and analysis can be found in Kanamitsu[1] and Parrish and Derber[2] respectively. The parameterization of the PBL in MAFS of the NCMRWF uses a simple first-order closure approximation. In addition, a non-local closure approximation for the PBL was implemented as a second boundary-layer parameterization in the MAFS. Both model versions having different schemes for the PBL (the rest of the physics and dynamics remaining the same) were run for five days with the same analysis, and the results were compared. The systematic errors for a one month run (February 1997) were also compared using both the schemes. The model having the non-local closure was utilized to study the marine boundary layer structure over the Arabian Sea.

Description of the schemes

PBL parameterization scheme of NCMRWF model

A short description of the model, which is run on an operational basis at NCMRWF, is given in Basu *et al.*[3]. The standard PBL parameterization uses a first-order closure approximation whereby the turbulent fluxes are correlated to the mean vertical gradients through the eddy diffusivities. These eddy diffusivities are stability-dependent (depending upon the bulk Richardson number) and are determined through mixing length considerations. It is assumed that the mixing length l varies as κz (κ being the von karman constant and z the height above the ground) close to the ground, but approaches constant value λ (= 250 m) at greater heights. Thus, the eddy diffusivities are determined through: $K = l^2 S\,|\partial v/\partial z|$ where l is the mixing length given by $l = \kappa z/(1 + \kappa z/\lambda)$. Here, S is a set of semi-empirical stability functions dependent upon the bulk Richardson number R, and λ is the limiting mixing length.

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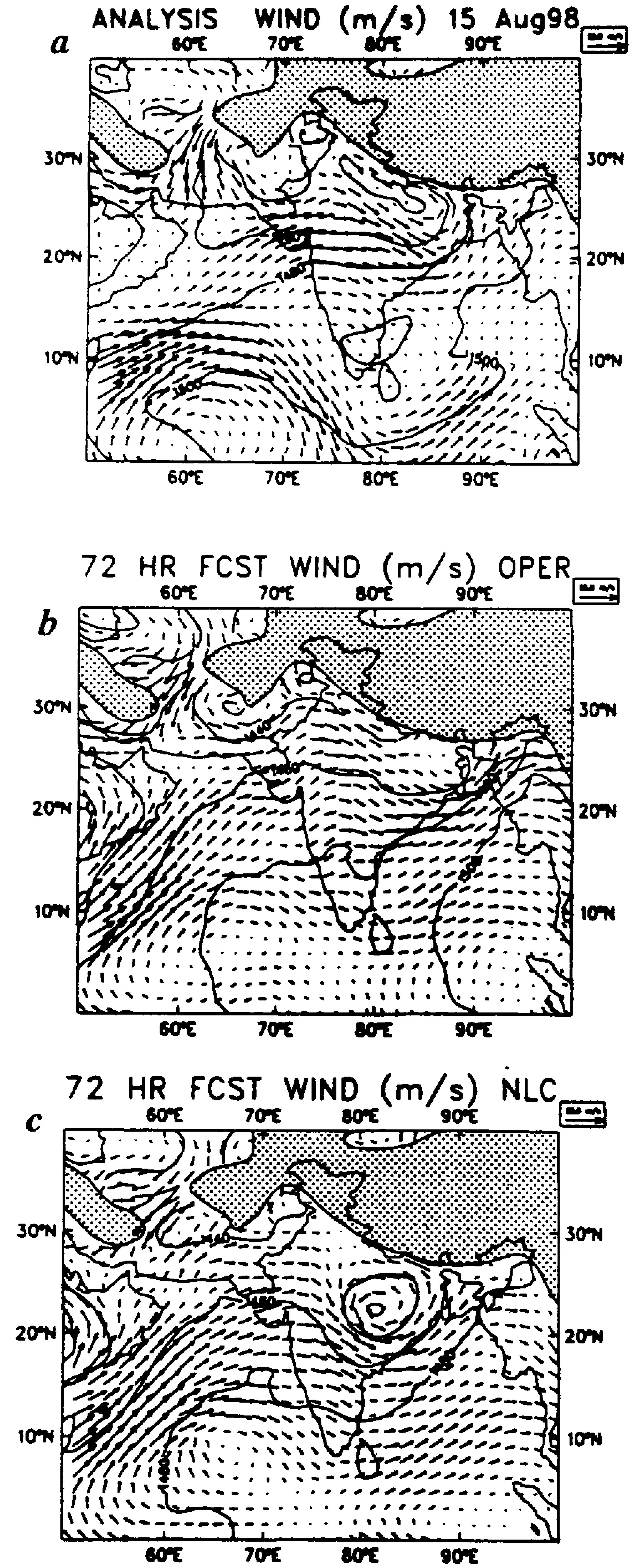

Figure 1. Variation of 850 hPa wind vectors and geopotential heights over monsoon region, ***a***, Verifying analysis (for 15 August 1998); ***b***, 72 h forecast by operational model (IC: 12 August 1998); ***c***, 72 h forecast by non-local closure (IC: 12 August 1998).

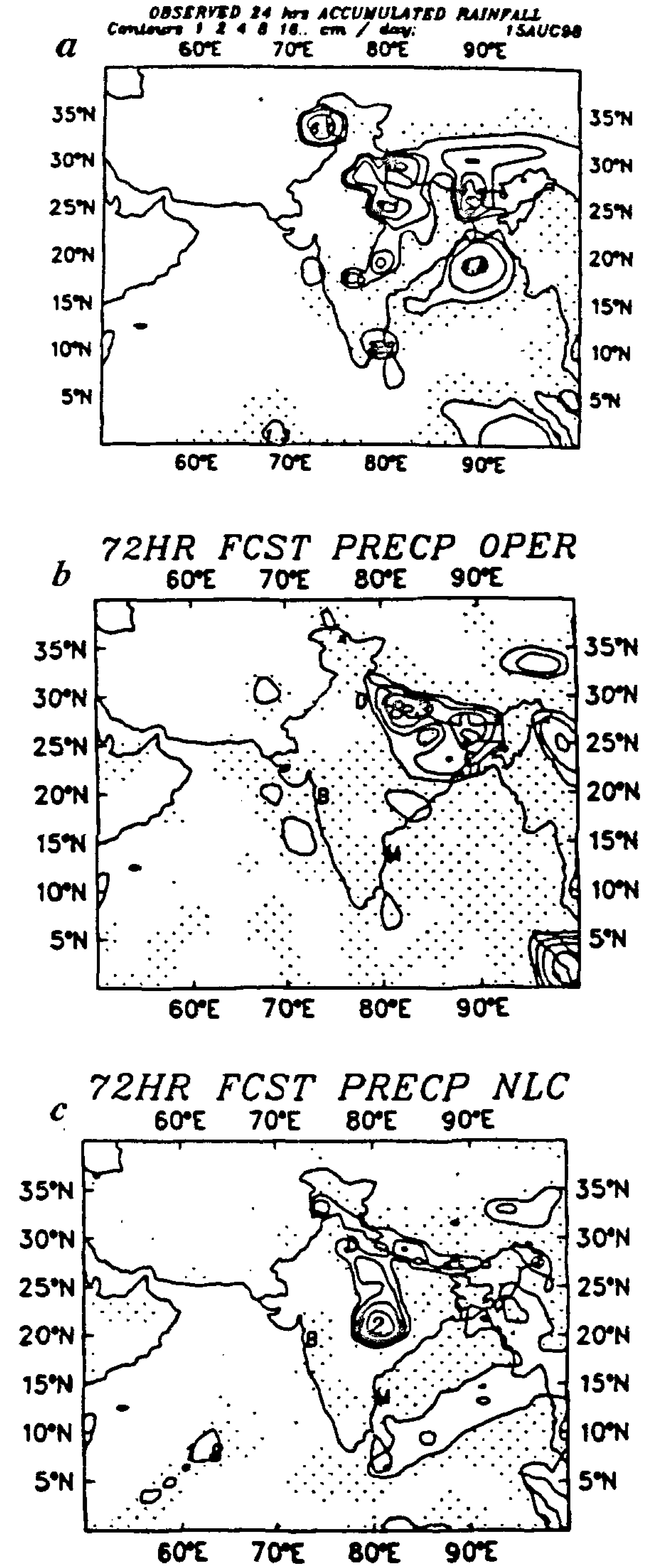

Figure 2. Geographical distribution of accumulated 48–72 h precipitation in cm over monsoon region. (min. contour 1 cm, shaded areas represent < 1 cm), ***a***, Analysed rainfall from OLR and rainguage; ***b***, 72 h forecast by operational model (IC: 12 August 1998); ***c***, 72 h forecast by non-local closure (IC: 12 August 1998).

Parameterization using the non-local closure scheme

There are certain limitations of the mixing length theory[4], the most important being its inability to represent realistically mixing in the convective boundary layer involving the 'counter gradient fluxes'[5–7]. One of the alternatives is to go to higher order closure approaches developed by Mellor and Yamada[8]. Mellor and Yamada level 1.5, 2.0 and 2.5 turbulence closure schemes have been tested and implemented for short-range forecast models[9–11]. They showed that though these schemes were capable of representing a well-mixed boundary layer structure, they were computationally more expensive. Moreover, Ayotte *et al.*[12] showed that these schemes were in the strictest sense local diffusion schemes and had a strong tendency to underentrain in the presence of a strong capping inversion. Recently an alternative approach has been suggested, the so-called non-local K closure, which is computationally efficient and has the capability to represent large eddy turbulence within a well-mixed boundary layer. This scheme[6,7] has been widely tested for general circulation models as well as numerical prediction models with further generalization and reformulation[13,14]. In the present study, the scheme that is used is after Hong and Pan[7], where the turbulence diffusion equations for prognostic variables (C, u, v, θ, q) are expressed by $\delta c/\delta t = \delta/\delta z[Kc(\partial C/\partial z - \gamma_c)]$, where K_c is the eddy diffusivity coefficient and γ_c is a correction to the local gradient that incorporates the contribution of the large scale eddies to the total flux. The diffusivity coefficient in the mixed layer is given by

$$K_m = k w_s z\,(l - z/h)^p,$$

where p is the profile shape exponent, w_s is the mixed layer velocity scale, h is the PBL height and k is the von karman constant. The PBL height is given by

$$h = R_{ib}\,\frac{\theta_{va}\,|U(h)|^2}{g(\theta_v(h) - \theta_s)},$$

where R_{ib} is the critical bulk Richardson number, $U(h)$ is the horizontal wind speed at h, θ_{va} is the virtual potential temperature at the lowest model level, $\theta_v(h)$ is the virtual potential temperature at h and θ_s is the appropriate surface temperature. For the free atmosphere, however, the local K approach is utilized.

Numerical experiments

Few case studies have been made with both PBL schemes during 1997–98. In the present work, however, results of only one such case are presented with initial condition of 12 August 1998 when a system that had formed over the Bay of Bengal had moved inland in a north-

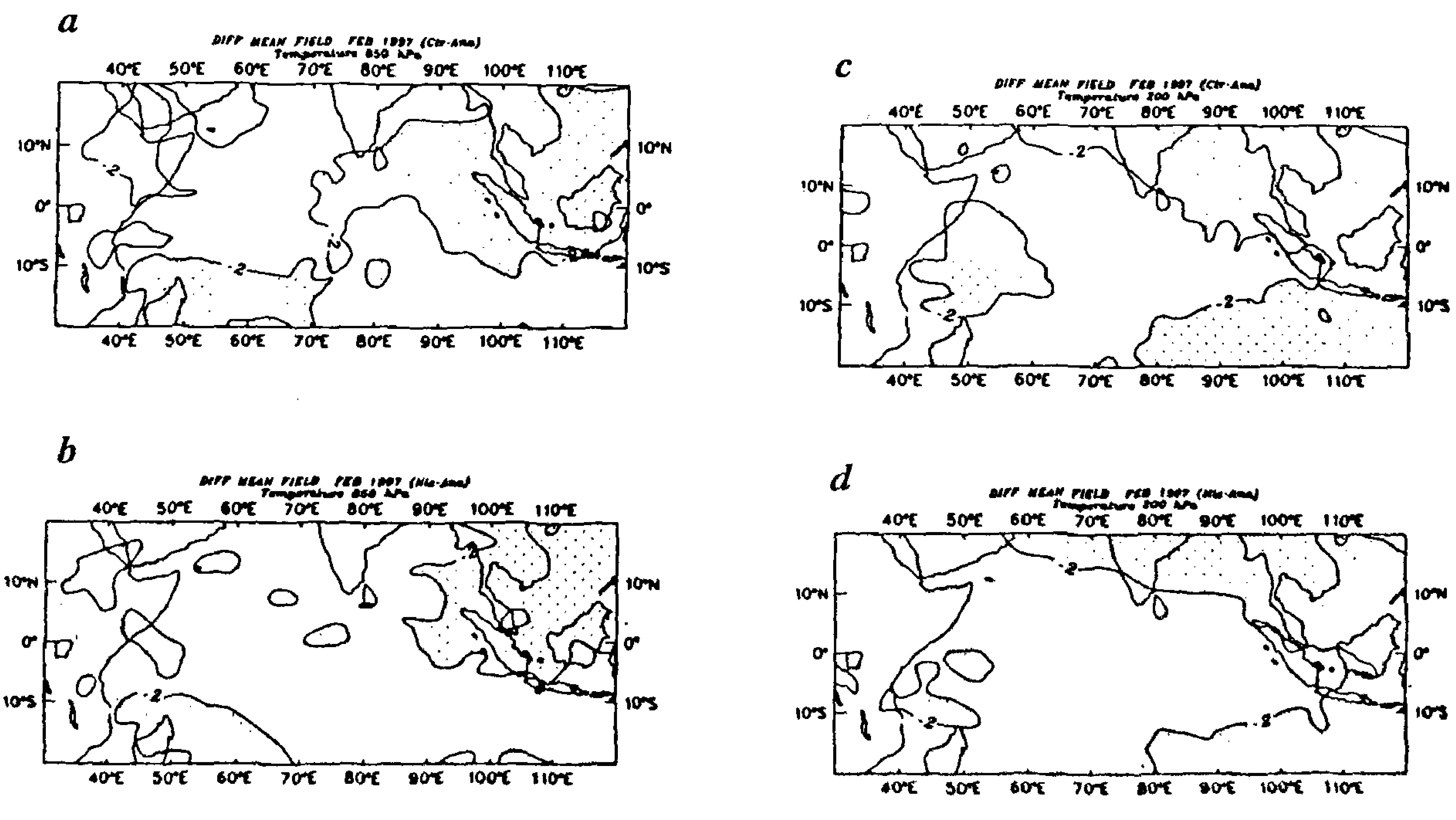

Figure 3. Systematic errors for temperature for February 1997. *a*, at 850 hPa with operational model; *b*, at 850 hPa by non-local closure; *c*, Same as (*a*) for 200 hPa; *d*, same as (*b*) for 200 hPa.

westerly direction resulting in precipitation over Delhi. Both the models having different parameterization for PBL only were run with the same initial condition, viz. 00 Z of 12 August 1998. The operational model having first order closure was neither able to predict the system (as seen in Figure 1 *b*) nor the rainfall over Delhi in the 72 h forecast (Figure 2 *b*). In contrast, the model having the non-local closure could predict the system reasonably as seen in Figure 1 *c* although the orientation or the exact location of the center does not match as compared to the verifying analysis (Figure 1 *a*). The model with non-local closure could also predict the rainfall pattern over Delhi well as shown in Figure 2 *c* when compared with the observed rainfall analysis[15]. Moreover, the general pattern of the rainfall distributions is also well-predicted including the patch over extreme northwest part by the non-local closure scheme which is not at all predicted by the operational model. Figures 3 *a* and *b* show the systematic errors of temperature for February 1997 at 850 hPa from the operational model and the model using the non-local closure. Figures 3 *c* and *d* show the errors at 200 hPa. The figures clearly bring out the superiority of the non-local closure scheme over the first order closure. In view of these results the model with the non-local closure scheme was utilized to simulate the marine boundary layer structure over the Arabian Sea for the INDOEX. Figures 4 *a* and *b* show the time evolution of the diffusivity profiles *Kh* and *Km* at 76.5°E, 14.4°N with the initial condition of 5 January 1997. It is seen that the maximum value of the diffusivities are occurring at a height of about 400 m and around 11.30 A.M. which is quite realistic. The maximum values attained are of the order of 100–200 m^2/s. Figures 5 *a* and *b* show the wind speeds and the wind direction profiles at the same location after 72 h of simulation with initial condition of 5 January 1997. It is seen that at the lower levels the winds are all easterlies (till 2000 m) beyond which the winds become south-easterlies as are generally observed. The wind speeds are also higher at the lower levels (of the order of 8–10 m/s) and before becoming south-easterlies it attains a minimum of about 4 m/s. Figures 6 *a* and *b* show the specific humidity and temperature profiles at the same location after 72 h of simulation with initial condition of 5 January 1997. Clearly, there is gradual decrease of humidity as well as temperature with height till 5000 m. Similar features were observed during cruise #120 (ref. 16). However, actual observational values at these locat0ions are required for proper validation of the model simulations. Figures 7 *a* and *b* show the temporal variation of boundary layer height at 76.5°E,

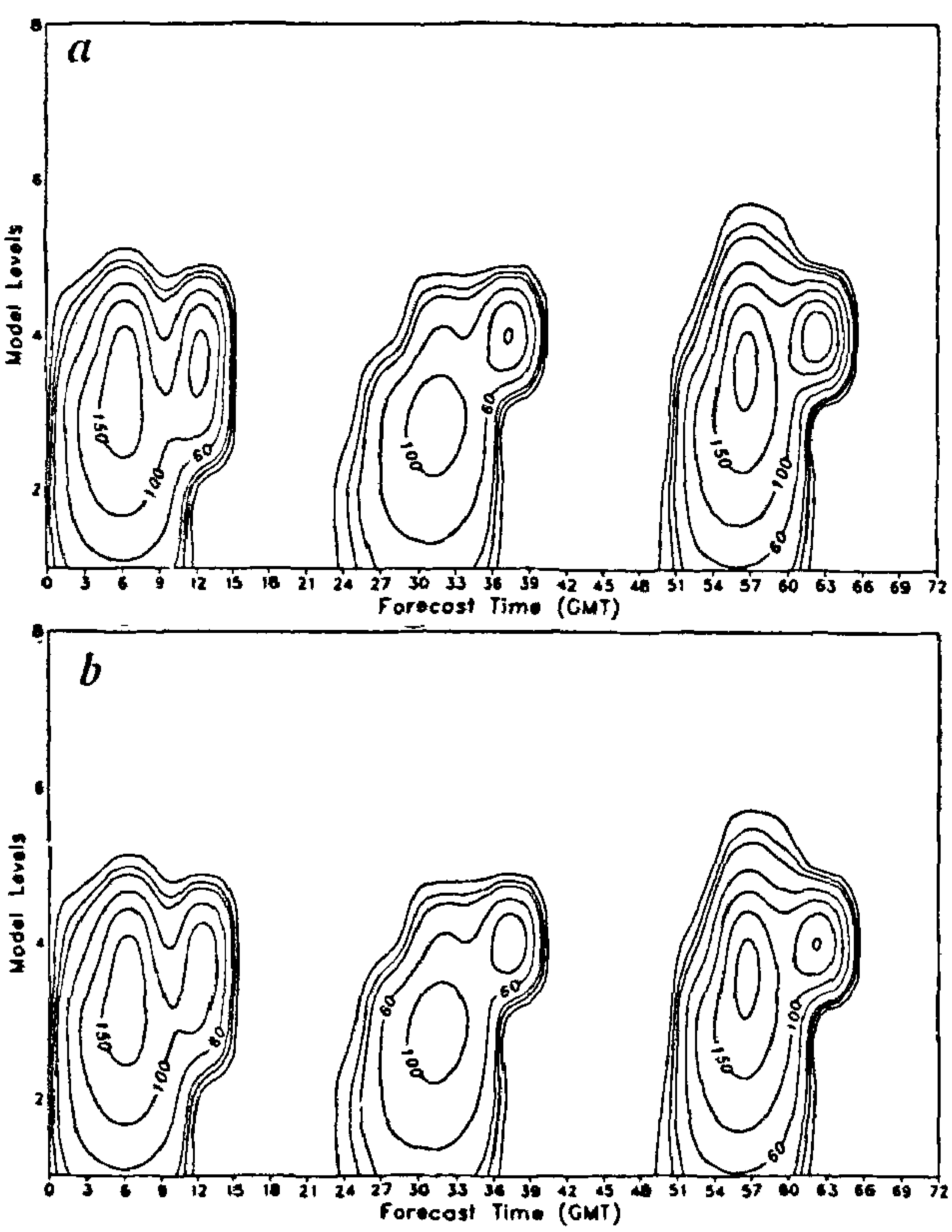

Figure 4. Time evolution of diffusivity profiles in m^2/s with IC: 5 January 1997: (*a*) for K_h; (*b*) for K_m.

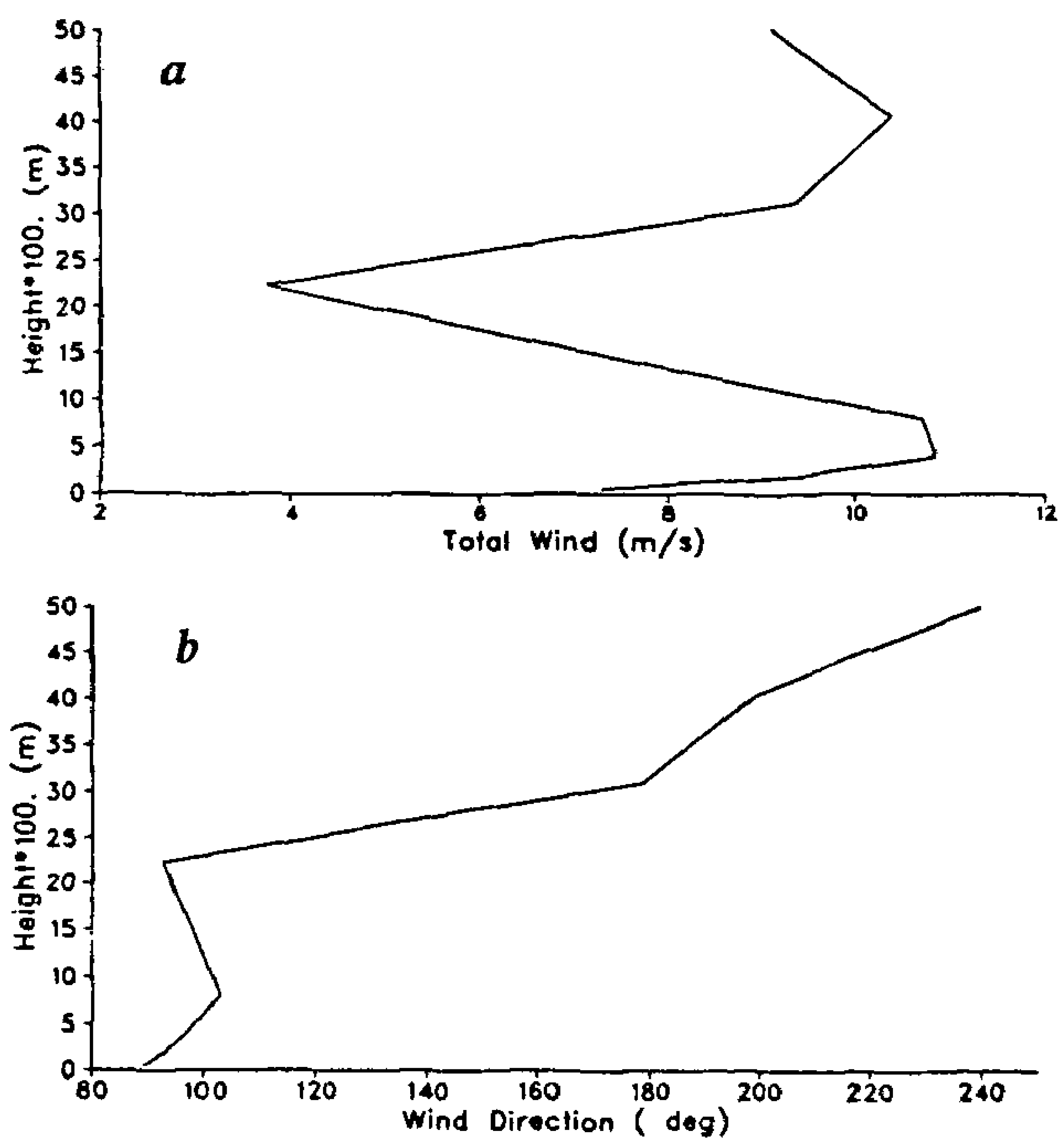

Figure 5. Profiles at 76.5°E, 14.4°N after 72 h forecast with IC: 5 January 1997 (*a*), Total wind in m/s; (*b*), Wind direction (deg).

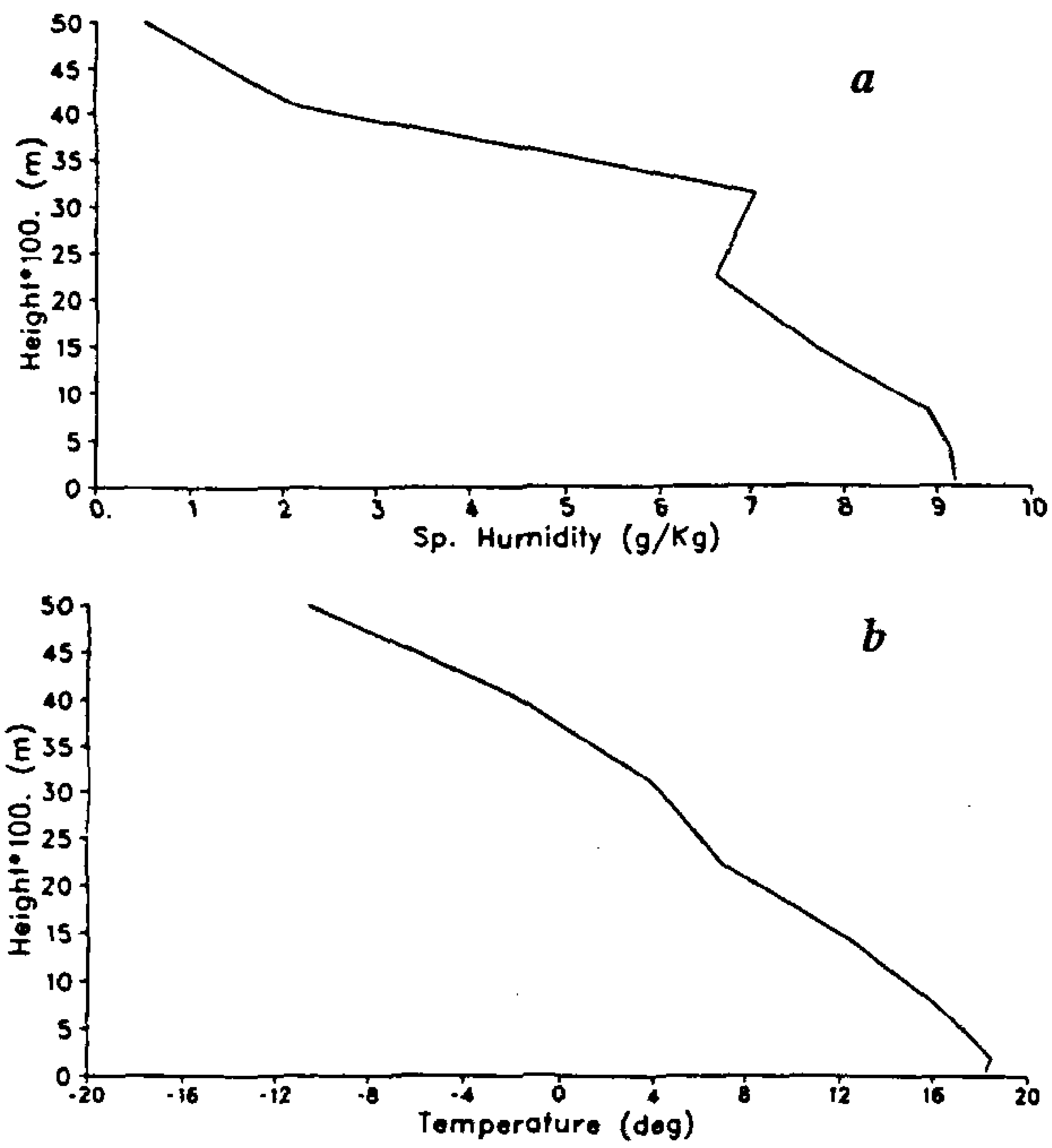

Figure 6. Profiles at 76.5°E, 14.4°N after 72 h forecast with IC: 5 January 1997. *a*, Specific humidity in g/kg; *b*, Temperature in °C.

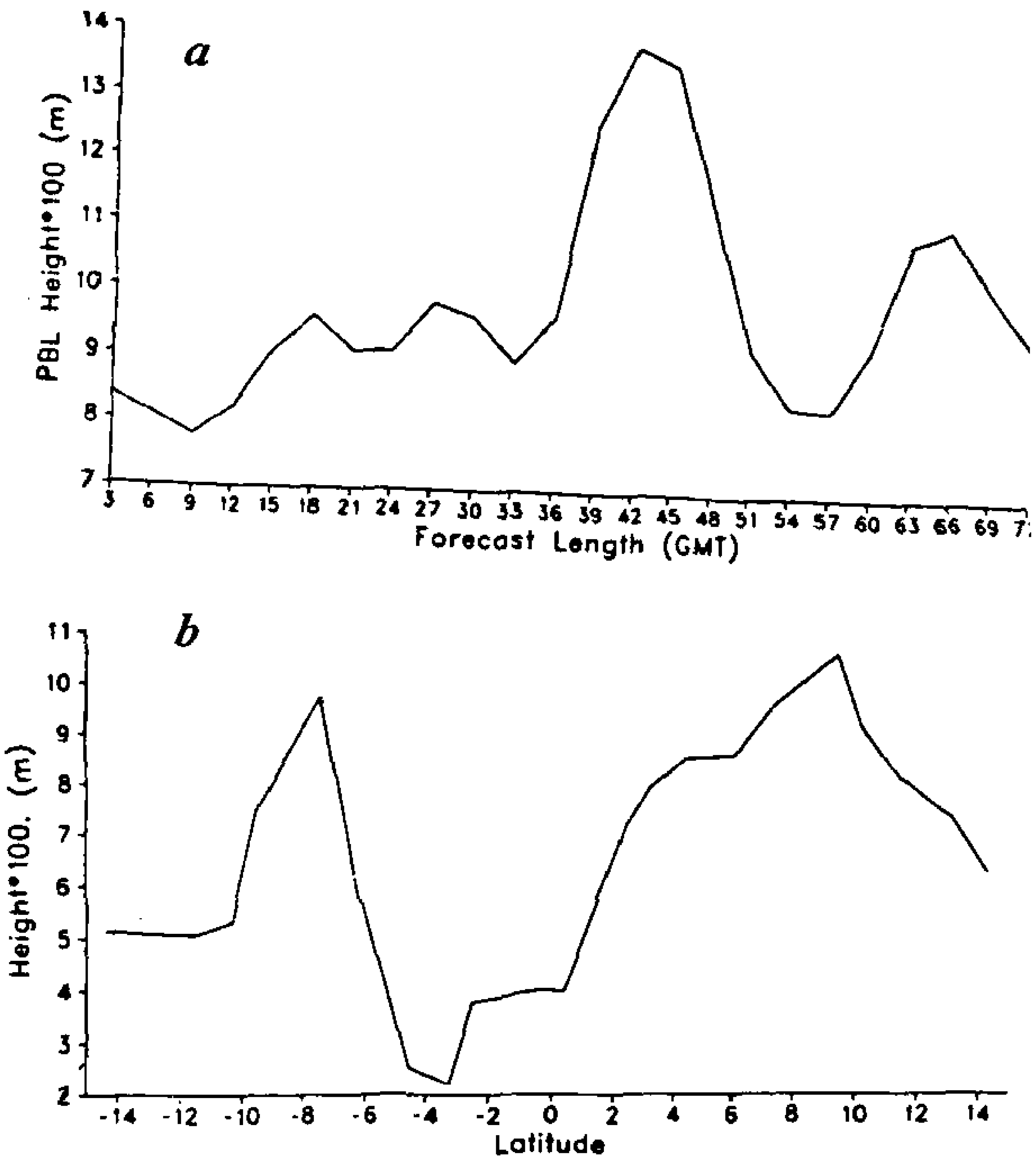

Figure 7. Variation of boundary layer height in m (76.5°E). *a*, temporal variation with IC: 5 January 1997 (6.18°N); *b*, Latitudinal variation after 72 h with IC: 5 January 1997.

6.18°N and latitudinal variation of boundary layer height at 76.5°E with initial condition of 5 January 1997. It is seen that there is a minimum value of the boundary layer height around 3°S with maximum around 10°N and 10°S. The temporal variation shows the boundary layer height attaining a maximum of 1400 m in the afternoon of 6 January, indicating higher convective activity. Observations from various cruises of INDOEX, however, would give confidence in the prediction of such important boundary layer parameters.

Conclusion

From the present study it is clear that the PBL parameterization has an impact in predicting general circulation features and precipitation patterns from a global spectral model. The model has the capability to reproduce the structure of the boundary layer over any region. It is important that these parameters produced by the model should be validated against observations obtained from programs like INDOEX so that confidence can be gained in using the model as a tool for predicting various features of the boundary layer over any region in the medium range scale.

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