# A Numerical Study of the Impact of Land Use Modification on Local Rainfall over Manila

by
Emmanuel G. Anglo and Roger A. Pielke

Department of Atmospheric Science
Colorado State University
Fort Collins, Colorado

Roger A. Pielke, P.I.
NSF Grant #ATM -8915265

Colorado State University

Department of Atmospheric Science

Paper No. 538

# A Numerical Study of the Impact of Land Use Modification on Local Rainfall over Manila

by

Emmanuel G. Anglo[1] and Roger A. Pielke[2]

## Abstract

Using a two-dimensional, nonhydrostatic and compressible version of the Colorado State University Regional Atmospheric Modelling System (CSU-RAMS), the impact of urbanization and deforestation in and around Manila, Philippines on its locally induced rainfall is investigated. Three sets of numerical experiments under varying synoptic conditions and using present, projected and fully vegetated land use were conducted. Twelve-hour simulations indicate significant differences in the strength, position and general behavior of convective activity between the three land use cases. Due mainly to reduced surface evapotranspiration and partly because of the strong controls exerted by the synoptic and topographic conditions on the response of the atmosphere to land use change, the present study did not reflect a direct increase of rainfall as a consequence of urbanization, in clear contrast to most measurements on the impact of urban growth. The weakness of the expected influence of urbanization in increasing rainfall reflected by the results may also be due to the neglect of increased CCN release by the city, which may be as important as the disruption of boundary-layer processes caused by urban land use modification. Nonetheless, the study clearly demonstrated the significant impact of land use changes on mesoscale circulations and subsequent rainfall patterns.

---

## 1. Background

Except for precipitation caused by large-scale disturbances, the local rainfall over the city of Manila in the Philippines comes primarily from convective clouds whose development is induced by

---

[1] Present affiliation: Department of Meteorology and Oceanography, College of Science, University of the Philippines, Diliman, Quezon City, Philippines 1101.

[2] Department of Atmospheric Science, Colorado State University, Fort Collins, Colorado, U.S.A. 80523.

two processes: sea breezes and topographic uplift. The first of these processes occurs due to the land-water temperature contrast between Manila Bay west of the city and the city itself. The convergence front associated with the sea breeze resulting from this contrast is often vigorous enough to lift moist air parcels to saturation. In the second process, the same result arises when air is forced over the mountains east of the capital either by sea breezes penetrating inland or by synoptic-scale winds.

Surface cover plays a critical role in these processes. The amount of incoming energy that the land surface absorbs and eventually releases is crucial to driving the sea breeze, so that changes in the type of soil and vegetation may alter the intensity of the circulation. In forced uplift, sensible heat flux from the surface is of secondary importance, but surface conditions remain vital because the amount of moisture available for cloud formation is partially determined by this factor. As recent numerical studies show, an important parameter to which the planetary boundary layer over land is most sensitive is a change in the intensity of surface evaporation. The sensitivity to surface vapor fluxes is such that mesoscale flow is easily perturbed, or may actually be initiated, by horizontal inhomogeneities in available soil moisture (Yan and Anthes 1988, Ookuchi et al 1984, Seaman et al 1989, Sun and Ogura 1979, Zhang and Anthes 1982), the type of underlying vegetation (Pinty et al 1989, Segal et al 1988, McCumber and Pielke 1981, Garrett 1982), or both (Mahfouf et al 1987, Smolarkiewicz and Clark 1985, Anthes 1984). Based on these studies, it may be claimed that the future trend in Manila's rainfall points to a decrease since the urbanization in a naturally forested region would be expected to reduce transpiration.

This conclusion, however, is contrary to the measurements conducted in connection with the METROMEX program, where it was found that urbanization in St. Louis, Missouri causes a perceptible increase in rainfall within and downwind of the city (Changnon et al 1981, Huff and Changnon 1986, Changnon and Huff 1986). This increase, as the study points out, is most likely induced by the following urban-related factors: an increase in the release of active CCN by the city, enhanced low-level convergence by increased roughness, intensified convection due to urban heating, and additional moisture release from industrial structures like cooling towers. Historical weather records between 1955-1970 from other urban cities in the U. S. gathered by Huff and Changnon (1973) also confirm this positive modification, manifested in more frequent morning thunderstorms and hailstorms. The enhancement was found to be proportional to the size of the city, industrial nuclei generation and urban thermal effects.

Landsberg (1981) summarizes numerous studies relating to the impact of urbanization on rainfall. It appears that while the increase of precipitation due to urbanization is theoretically plausible and is supported by observations, historical data is hardly unanimous about this conclusion. Rainfall comparisons between several urban cities and the rural areas that surround them do reflect higher values over the city, but the differences are below the standard deviation of annual precipitation in each. In some cities where comparisons were made of rainfall before and after urbanization, e. g. Tel Aviv and Naples did reflect a positive anthropogenic influence, but not all areas screened for this possibility yielded the same result. The same reference also cited studies showing higher rainfall on weekdays against weekends, pointing to the higher CCN concentrations caused by industrial activity as a more dominant factor responsible for the precipitation enhancement. The inconsistency of observational results reflects both the importance of particularities in each situation such as topography and climate, as well as the inherent intricacy of the problem.

Because conclusions about the impact of urbanization on precipitation valid in one area is not readily applicable to another, any projection regarding possible consequences on rainfall by the city of Manila cannot be made simply by looking at results of studies conducted elsewhere. In addition, although some measurements of rainfall over Manila are available from which trends may be seen, it is difficult to isolate the exact amount of precipitation induced by local processes (and influenced by urbanization) from that caused by larger systems. Numerical modelling may provide a tentative estimate of the impact of land use change until more theoretical and empirical studies become available.

## 2. The Climate of Manila

Manila is the capital and the largest city in the Philippines, an archipelago in the western Pacific. It is within the domain of the Asian monsoon, which manifests itself in the area as winds reversing from southwesterly during summer and northeasterly during winter. During the summer monsoon, the moist layer is about 10 km deep, conditionally unstable with no pronounced inversion (Flores and Balagot 1978). During winter, a moderate inversion usually appears around 1500 m and the atmosphere is much drier than during summer. Short transition periods between these seasons are dominated either by relatively dry westerly winds intruding from the midlatitudes or the moisture-laden North equatorial trades.

Figs. 1-3 represent nearly 100 years of standardized rainfall records over Port Area in Manila (the gap covers World War II). Eleven-year moving averages for each season were computed and are indicated by the dotted line in each map.

Rainfall trends during the SW Monsoon season (Fig. 1) differ greatly from those during the NE Monsoon (Fig. 2). A strong positive rainfall anomaly was registered during the summers before 1920 up to mid-1930, but winter records do not reflect the same increase. Because most precipitation is experienced during the SW monsoon, the annual totals also show this large rise. Post-war records also show a period of relatively wet years and summers between mid-1950s to mid-1970s but this again is not exhibited by NE monsoon rainfall.

Starting from the early 1970s, urbanization has been accelerating in Manila and its surroundings. Coincident to this modernization is an apparent sharp decrease in summer and annual rainfall over the area. It cannot, however, be ascertained if this reduction is at all due to land-use change because the strong 1982-83 El Niño episode that caused a severe drought in the Central

Luzon region reduces the moving average for the period.

The assessment of the effects of urbanization and deforestation is important to environmental planners, health officials and weather forecasters. To perform such an assessment for a locality where few measurements are available, one method commonly used is energy-balance climate modelling. Models of this type, however, are more useful in estimating long-term mean conditions on large scales rather than describing phenomena in the shorter time and space scales required to investigate the local weather effects of urbanization. Because weather patterns in the city are dominated by diurnally fluctuating systems, mesoscale numerical models are more appropriate in evaluating the effect of changes in surface conditions brought about by urbanization on Manila´s future rainfall.

It is projected that the change in urbanization of Manila will come mainly as an increase in size rather than further intensive development within its present boundaries. Also, this expansion is expected to be accompanied by an increase of the area at the periphery of Manila dedicated to farming as a response to the food demands of the increasing city population. These changes are reflected in the experiments described in the next section.

Since other thermal properties of the urban boundary layer are reasonably well understood, this study focuses mainly on the cloud and precipitation processes. In particular, the following questions are addressed:

(i) Will the reduction of available surface moisture due to paving and the removal of vegetation suppress cumulus development, or will the presence of the bay as a source of water vapor prevent any such result?

(ii) If the heat island warms up and enhances convection over the city, will expected rainfall from cumulus clouds increase?

## 3. Computational Methodology

Three sets of numerical experiments were conducted to answer the questions previously posed. Each set reflects different synoptic wind conditions: southwesterly, northeasterly and calm. In each set, the first case (Case 1) served as the control, simulating atmospheric conditions over Metro Manila under present land use. The second case (Case 2) used projected land use patterns by assuming urbanization in areas beyond Manila´s present boundaries, including added farming on the eastern shores. As an additional experiment to determine how much present land use in Manila has already altered its rainfall, a third case (Case 3) incorporating conditions prior to urbanization was also conducted.

The model used was a version of the Colorado State University Regional Atmospheric Modelling System (e. g., see Tremback et al 1986). The model has proven capable of simulating various types of mesoscale flow and has found wide application in research from cloud microphysics to air pollution modelling.

For all three sets of experiments, a three-dimensional, nonhydrostatic compressible version of the CSU-RAMS model was tested with the following specifications:

(i) Subgrid-size eddy turbulence exchange were parameterized using a Smagorinsky-type formulation.

(ii) Cloud microphysics formulations followed Tripoli and Cotton (1980), which contains such processes as conversion and accretion of cloud water to raindrops, and the evaporation and gravitational settling of these raindrops. Ice processes such as melting, sublimation, freezing and deposition were also included. Mixing ratios of rain water, pristine crystals and aggregates were explicitly predicted.

(iii) The radiative model was based on the shortwave and longwave radiation model of Mahrer and Pielke (1977) which incorporates the role of Rayleigh scattering, water vapor absorption and terrain slope.

(iv) The present version employed the soil model of Tremback and Kessler (1985), and the vegetation parameterization of Avissar and Mahrer (1988).

A 67 x 41 two-dimensional grid oriented southwest to northeast across Manila with 2 km horizontal spacing was used (Fig. 4). Vertical spacing was 250 m and the time step was 10 s. Predictions were carried up to twelve hours from an initial local time of 0600. The initialization used horizontally homogeneous profiles of parameters taken from average soundings during the months of July and August for the southwest monsoon and the calm wind cases, and January-February mean soundings for the northeast monsoon simulations.

## 4. Results and Discussion

### a. *Southwest Monsoon Cases*

Results after twelve hours of simulation for this set are shown in Fig. 5. In case 1, most convective activity is a result of forced uplift, but a strong speed-up along the lee side of the island is met by opposing sea-breezes, causing strong convergence. A separate region for convection has thus formed near the lee side of the eastern peak.

In case 2, The wind field is not significantly different from that in case 1 as far as convergence regions, but there is a distinct strengthening of both positive and negative vertical velocities. The enhancement of convection at the middle peak is evidently caused by the transition zone between vegetated and urbanized land. In the other regions, the enhancement may have been initiated by the intensification of convection at the moist-dry land interface.

There is a large difference in the rain mixing-ratio distribution shown in the two cases. In case 2, even if vertical velocities are stronger, rainfall, in general, is more localized and is restricted to the western peak. Clearly, the increased vertical velocities enhance condensation in this region at the expense of that over the eastern side of the domain.

Comparing the first case to the third (pre-urban) case, the more even distribution of rainfall is conspicuous in the pre-urban environment. Four distinct areas of significant precipitation may be identified: the westernmost is most likely the result of a sea-breeze embedded in the background flow, and the other three due to topographic uplift. In those convective areas caused by uplift, there is a clear reduction of condensate as one progresses eastward, because moisture available for condensation is rained out upwind.

### *b. Northeast Monsoon Cases*

In Fig. 6, smaller rainfall results were obtained in the Northeast monsoon simulations because the atmosphere was much drier. In all three cases, all moist convection came as a result of mechanical uplift so that only the two upwind peaks received precipitation. In case 2, a considerable reduction of rainfall in the eastern peak occurred as a result of the replacement of forest cover with crop farming. Except for this difference, all other fields between the two cases were almost identical.

Between case 1 and case 3, very little difference may be discerned. Because most changes in land use occur on the lee side of the western slope, no impact on rainfall is seen.

### *c. Calm Wind Cases*

Strongest rainfall were obtained in this set (Fig. 7) of simulations because the island was small enough to allow the sea-breeze fronts that formed on its two sides to combine to form a very intense convective region. In case 1, most convective activity was in fact the result of this type of uplift rather than purely topographic, giving rise to a symmetric distribution of the meteorological fields.

In case 2, symmetry is somewhat reduced, but the strong convective region in the middle of the domain is still present. Both vertical velocities and rainfall are weaker in this case, a result of the reduction of evaporation from the surface due to increased urbanization on the west and deforestation on the east.

Case 3 fields are the most symmetric, but vapor mixing-ratio contours exhibit a deeper and more well-mixed moist layer over the western side than the eastern. Because this inequality is primarily a boundary layer feature and no inhomogeneities are present in the soil type and vegetative cover, the asymmetric topographic heights are seen as the cause of this variability.

From the same results, the present degree of urbanization appears to have had only a weak but noticeable impact on previous precipitation patterns. But with a doubling of the present degree of urban land use as depicted in case 2, a large reduction of rainfall from the pre-urban case should occur. This observation, however, is valid only for this particular local time, as the next section will indicate that rainfall prior to this time for this case is considerably higher than for the other two cases.

### *d. 12-Hour Rainfall*

Total precipitation after twelve hours of simulations are plotted in Figs. 8-10 for all nine cases. In the southwest monsoon simulations, the shift from present land use to further urbanization seems to have an impact on rainfall that cannot be defined in simple terms as different positions in the domain reflect contradictory trends. For example, upwind of the western peak a slight future increase is revealed (Fig. 8). Immediately upwind, however, a decrease is evident. Domain totals reveal a general decrease amounting to about 5% of present values.

The same figure also indicates that since pre-urban times there has already been a decrease in rainfall over large parts of the domain, which is shown to be about 10% for the entire region. And yet the middle of the domain reflects a definite increase. Apparently, while the reduction of vegetative cover would diminish the amount of available moisture, the appearance of inhomogeneities in surface conditions would complicate the effect of this reduction on rainfall by introducing new regions for convergence.

For the northeast monsoon cases, future land use is predicted to reduce rainfall for that season by 40% as denoted by the domain totals in Fig. 9. This decrease is mainly over the upwind region and is therefore more an effect of farming over the eastern shores and less the result of urbanization over Manila. This is confirmed by a comparison of cases 1 and 3 which exhibits no difference in twelve-hour rainfall.

The third set of calm-wind experiments do not, however, correspond with the second experiment. In this set, future land use appears to *increase* by 3% present total domain rainfall in relation to present levels (Fig. 10). This increase is found mainly over the eastern half of the domain, accompanied by a decrease on the western side.

Past rainfall levels are also higher in this experiment than in the present, but they are slightly lower than in the projected.

In fact, throughout the domain, case 3 levels fall consistently between the levels of the other two cases. This indicates that the rearrangement of surface cover would increase rain in some regions at the expense of others, although as the domain totals disclose, evapotranspiration remains an important factor determining the aggregate amount that is expected in each case.

To clarify further why an increase was predicted for future land use, results after six hours of simulations are presented in Fig. 11. These figures show that apart from the convective region generated by topographic uplift, a secondary convective region develops at the interface between forest and farmland. Apparently, in calm wind conditions the difference between the thermal properties of these two types of surface cover is sufficient to permit strong gradients to independently induce convection, or enhance those caused by other "regular" processes. Although this new system soon dissipates, its contribution to accumulated rainfall remains substantial. It must be noted that no such cell formed at the urban-vs.-forested interface (present land use conditions), probably because the bare soil contained too little moisture to allow it to develop.

## 5. Conclusion

The impact of urban land use change over Metro Manila and its surroundings on the rainfall induced by mesoscale processes in the vicinity is revealed by numerical modelling to be more complex than just an overall qualitative increase as previous measurements and modelling studies on other urban areas would show. During the humid synoptic conditions of the southwest monsoon, present land use appears to have already caused a large rearrangement of convective activity, concentrating rainfall on the urban-vs.-forested soil interface. Further urbanization and deforestation is predicted by the model to enhance precipitation on the upwind side of the island at the expense of the rest of the region. During the northeast monsoon when the atmosphere is much drier, the impact is less intense, although rainfall is expected to decrease due to future surface conditions. Present urban land use has slightly reduced rainfall under calm winds than if land were fully vegetated, but future crop farming should cause the appearance, early in the diurnal cycle, of productive convection where forested land meets farmland.

While the simulations agree with the results of previous numerical studies on the sensitivity of mesoscale flow to soil and vegetation conditions, and are weakly corroborated by actual rainfall records over Manila, the results remain different from measurements of possible urban-induced precipitation modification. The present results showing a reduction is an obvious consequence of the lower available surface moisture in urban surface cover. Because most convection occurs over the land areas, the presence of the bodies of water around the island fails to negate this reduction. Simulations for a smaller island, however, may yield an answer to the first question (posed earlier in this paper) different from those obtained in this effort.

Regarding the second question concerning the impact of the observed enhancement of convection over a city due to its higher temperatures, it appears that in the presence of background synoptic winds, terrain elevations adjacent to Manila provide strong mechanisms for lifting air parcels to saturation that weaken the effects of the urban presence on rainfall. Any convection region formed due to inhomogeneities in soil and vegetation (i. e. physiographic mesoscale circulations) remains secondary to convection forced by topography. Only when sea breezes or background winds are weak would such systems be significant, as manifested in the cell that formed at the forested-vs.-farmland interface in the early stages of the calm wind case.

The ability of the model to reflect the influence of urban land use on rainfall is limited by the disregard for other phenomena associated with urbanization. In particular, the inclusion of a parameterization for the change in CCN concentration could have counteracted the impact of the removal of vegetation over the urban area. Further studies that incorporate this highly variable quantity may be crucial to defining the true impact of urbanization on convective activity.

*Acknowledgments.* This research was completed as part of NSF Grant no. ATM-8915265 . The authors would like to thank the NCAR for the use of their supercomputer facilities; NCAR is supported by the National Science Foundation. The senior author was a visiting scientist at Colorado State University on a Fulbright-Hays fellowship. Many thanks to John Lee for his generous help with the CSU-RAMS and Dallas McDonald for typing the manuscript. Jorge de las Alas and Israel Bentillo gave useful suggestions regarding the output.

# REFERENCES

Anthes, R. A., 1984: Enhancement of convective precipitation by mesoscale variations in vegetative covering in semiarid regions. *J. Clim. Appl. Meteor.*, **23**, 541-554.

Avissar, R. A., and Y. Mahrer, 1988: Mapping frost-sensitive areas with a three-dimensional local-scale numerical model: physical and numerical aspects. *J. Appl. Meteor.*, **27**, 400-413.

Changnon, S. A., Jr., Ed., 1981: *METROMEX: A Review and Summary. Meteor. Monogr.*, No. 40, Amer. Meteor. Soc., 181 pp.

-------- and F. A. Huff, 1986: The urban-related nocturnal rainfall anomaly at St. Louis. *J. Clim. Appl. Meteor.*, **25**, 1985-1995.

Flores, J. F., and V. F. Balagot, 1978: Climate of the Philippines. *Climates of Northern and Eastern Asia*, H. Arakawa, Ed., Elsevier, pp. 159-213.

Garrett, J. H., 1982: A parameter study of interactions between convective clouds, the convective boundary layer, and a forested surface. *Mon. Wea. Rev.*, **110**, 1041-1059.

Huff, F. A., and S. A. Changnon, Jr., 1973: Precipitation modification by major urban areas. *Bull. Amer. Meteor. Soc.*, **54**, 1220-1232.

-------- and --------, 1986: Potential urban effects on precipitation in the winter and transition seasons at St. Louis, Missouri. *J. Clim. Appl. Meteor.*, **25**, 1887-1907.

Landsberg, H. E., 1981: *The Urban Climate.* Academic Press, 277 pp.

Mahfouf, J. F., E. Richard and P. Mascart, 1987: The influence of soil and vegetation on the development of mesoscale circulations. *J. Clim. Appl. Meteor.*, **26**, 1483-1495.

Mahrer, Y., and R. A. Pielke, 1977: A numerical study of the airflow over irregular terrain. *Contrib. Atmos. Phys.*, **50**, 98-113.

McCumber, M. C., 1981: Simulation of the effect of surface fluxes of heat and moisture in a mesoscale numerical model. Part I: Soil layer. *J. Geophys. Res.*, **86**, 9929-9938.

Ookuchi, Y., M. Segal, R. C. Kessler and R. A. Pielke, 1984: Evaluation of surface effects on the generation and modification of mesoscale circulations. *Mon. Wea. Rev.*, **112**, 2281-2292.

Pinty, J.-P., P. Mascart, E. Richard and R. Rosset, 1989: An investigation of mesoscale flows induced by vegetation inhomogeneities using an evapotranspiration model calibrated against HAPEX-MOBILHY data. *J. Appl. Meteor.*, **28**, 976-992.

Seaman, N. L., F. L. Ludwig, E. G. Donall, T. T. Warner and C. M. Bhumralkar, 1989: Numerical studies of urban planetary boundary-layer structure under realistic synoptic conditions. *J. Appl. Meteor.*, **28**, 760-781.

Segal, M., R. Avissar, M. C. McCumber and R. A. Pielke, 1988: Evaluation of vegetation effects on the generation and modification of mesoscale circulations. *J. Atmos. Sci.*, **45**, 2268-2292.

Smolarkiewicz, P. K., and T. L. Clark, 1985: Numerical simulation of the evaluation of a three-dimensional field of cumulus clouds. Part I: Model description, comparison with observations and sensitivity studies. *J. Atmos. Sci.*, **42**, 502-522.

Sun, W.-Y., and Y. Ogura, 1979: Boundary-layer Forcing as a possible trigger to a squall-line formation. *J. Atmos. Sci.*, **36**, 235-253.

Tremback, C. J., and R. C. Kessler, 1985: A surface temperature and moisture parameterization for use in mesoscale numerical models. *Preprints, 7th Conference on Numerical Weather Prediction*, 17-20 June 1985, Montreal, Canada, Amer. Meteor. Soc.

Tripoli, G. J., and W. R. Cotton, 1982: The Colorado State University three-dimensional cloud/mesoscale model - 1982. Part 1: General theoretical framework and sensitivity experiments. *J. de. Rech. Atmos.*, **16**, 185-220.

Yan, H., and R. A. Anthes, 1988: The effect of variations in surface moisture on mesoscale circulations. *Mon. Wea. Rev.*, **116**, 192-208.

Zhang, D., and R. A. Anthes, 1982: A high resolution model of the planetary boundary layer - sensitivity tests and comparisons with SESAME-79 data. *J. Appl. Meteor.*, **21**, 1594-1609.

## List of figures and captions

Fig. 1. Standardized annual rainfall at Port Area, Manila during the SW monsoon. Dotted line indicates 11-year moving average. (Courtesy of R. Buan)

Fig. 2. Same as Fig. 1, but the the NE monsoon.

Fig. 3. Same as Fig. 1, but for annual totals.

Fig. 4. Low-resolution topographic map of Manila and vicinity. Contours are drawn at 250-m intervals. Thick line indicates the orientation of two-dimensional grid used; shading defines present extent of urban area.

Fig. 5. Results of SW monsoon experiments at 1800 LST. Case 1 (present land use) results are on the left column, case 2 (projected land use) on the middle, and case 3 (fully forested) on the right. From top row: $u$ (contours drawn at 2 $ms^{-1}$ intervals), $w$ ($2x10^{-1}$ $ms^{-1}$), potential temperature ($2K^{\circ}$), vapor mixing ratio (10 $gkg^{-1}$), and rain mixing ratio ($1x10^{-1}$ $gkg^{-1}$).

Fig. 6. Same as Fig. 5, but for NE monsoon experiments.

Fig. 7. Same as Fig. 5, but for calm wind experiments. Vertical velocity results (second row from top) drawn at 1 $ms^{-1}$ intervals, rain mixing ratios (bottom) at $2x10^{3}$ $gkg^{-1}$ intervals.

Fig. 8. Total 12-hour rainfall along x-axis for SW monsoon experiments. Solid line is for fully forested case, dashed line for present land use, dotted line for projected. Totals for entire domain in each case are indicated in inset.

Fig. 9. Same as Fig. 8, but for NE monsoon experiments. Note change in range along abscissa.

Fig. 10. Same as Fig. 8, but for calm wind experiments.

Fig. 11. Same as Fig. 5, but for 1200 LST, calm wind experiments.

# List of figures and captions

Fig. 1. Standardized annual rainfall at Port Area, Manila during the SW monsoon. Dotted line indicates 11-year moving average. (Courtesy of R. Buan)

Fig. 2. Same as Fig. 1, but the the NE monsoon.

Fig. 3. Same as Fig. 1, but for annual totals.

Fig. 4. Low-resolution topographic map of Manila and vicinity. Contours are drawn at 250-m intervals. Thick line indicates the orientation of two-dimensional grid used; shading defines present extent of urban area.

Fig. 5. Results of SW monsoon experiments at 1800 LST. Case 1 (present land use) results are on the left column, case 2 (projected land use) on the middle, and case 3 (fully forested) on the right. From top row: $u$ (contours drawn at 2 ms$^{-1}$ intervals), $w$ (2x10$^{-1}$ ms$^{-1}$), potential temperature (2K$^{o}$), vapor mixing ratio (10 gkg$^{-1}$), and rain mixing ratio (1x10$^{-1}$ gkg$^{-1}$).

Fig. 6. Same as Fig. 2, but for NE monsoon experiments.

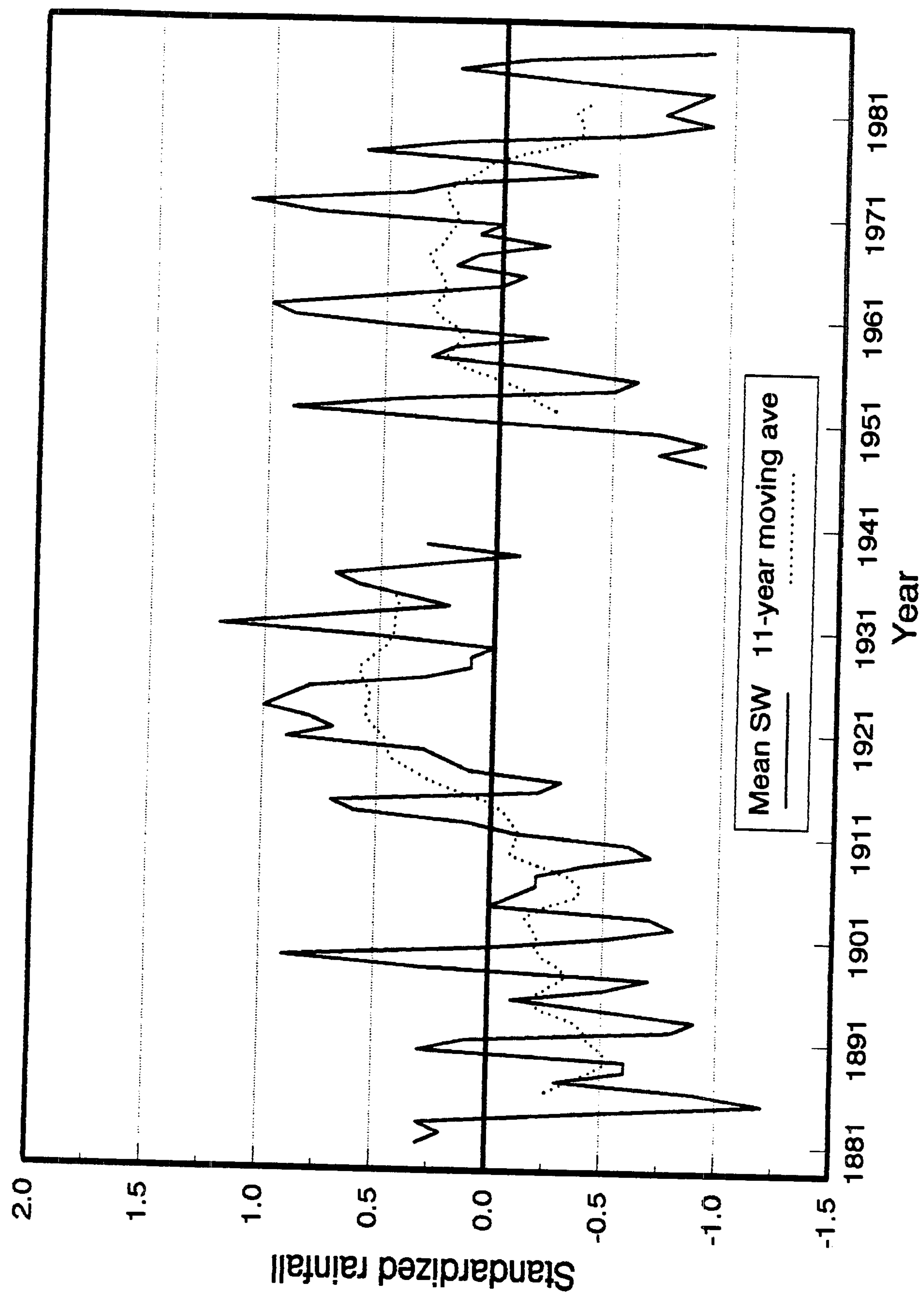
Fig. 7. Same as Fig. 2, but for calm wind experiments. Vertical velocity results (second row from top) drawn at 1 ms$^{-1}$ intervals, rain mixing ratios (bottom) at 2x10$^{3}$ gkg$^{-1}$ intervals.

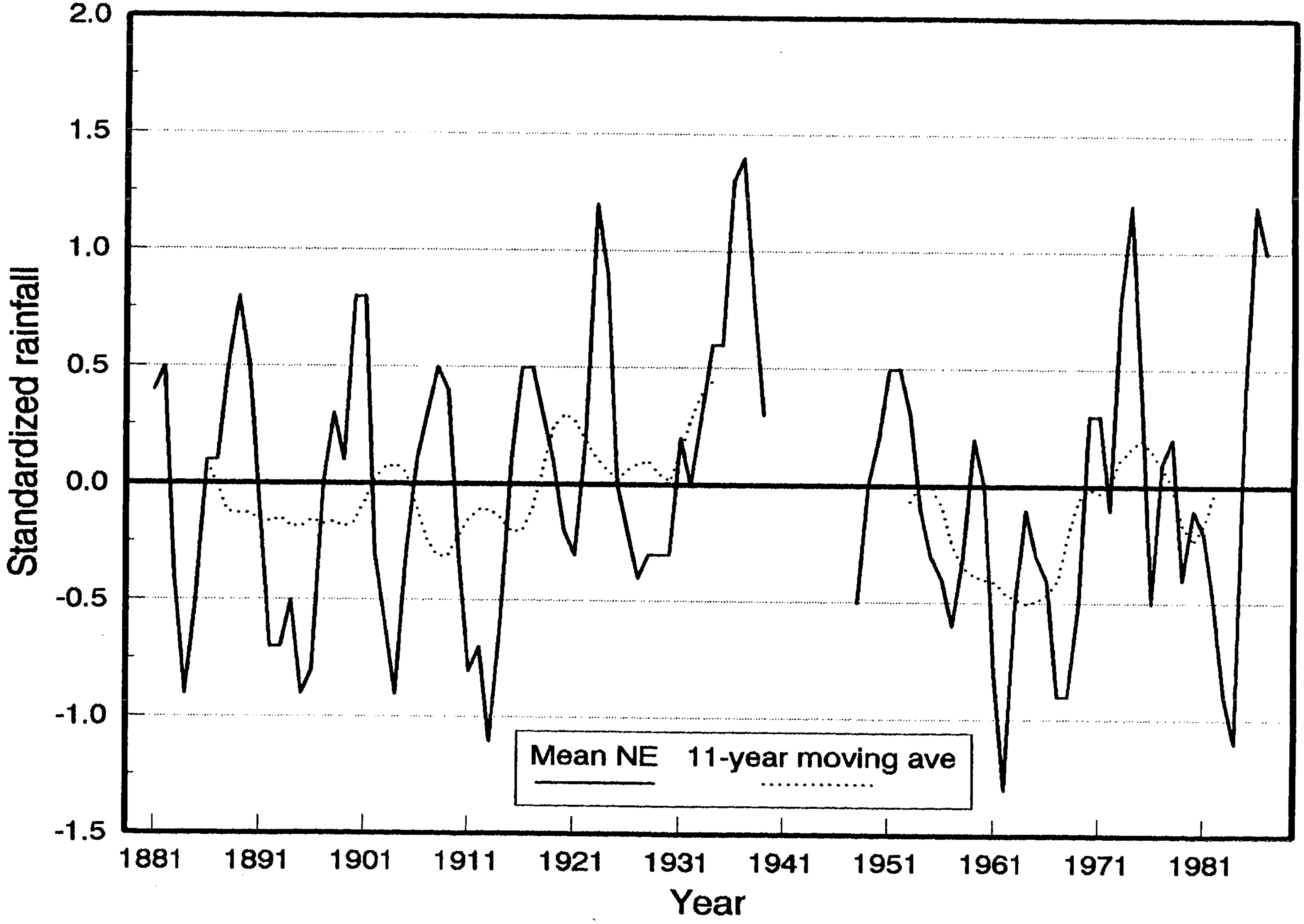
Fig. 8. Total 12-hour rainfall along x-axis for SW monsoon experiments. Solid line is for fully forested case, dashed line for present land use, dotted line for projected. Totals for entire domain in each case are indicated in inset.

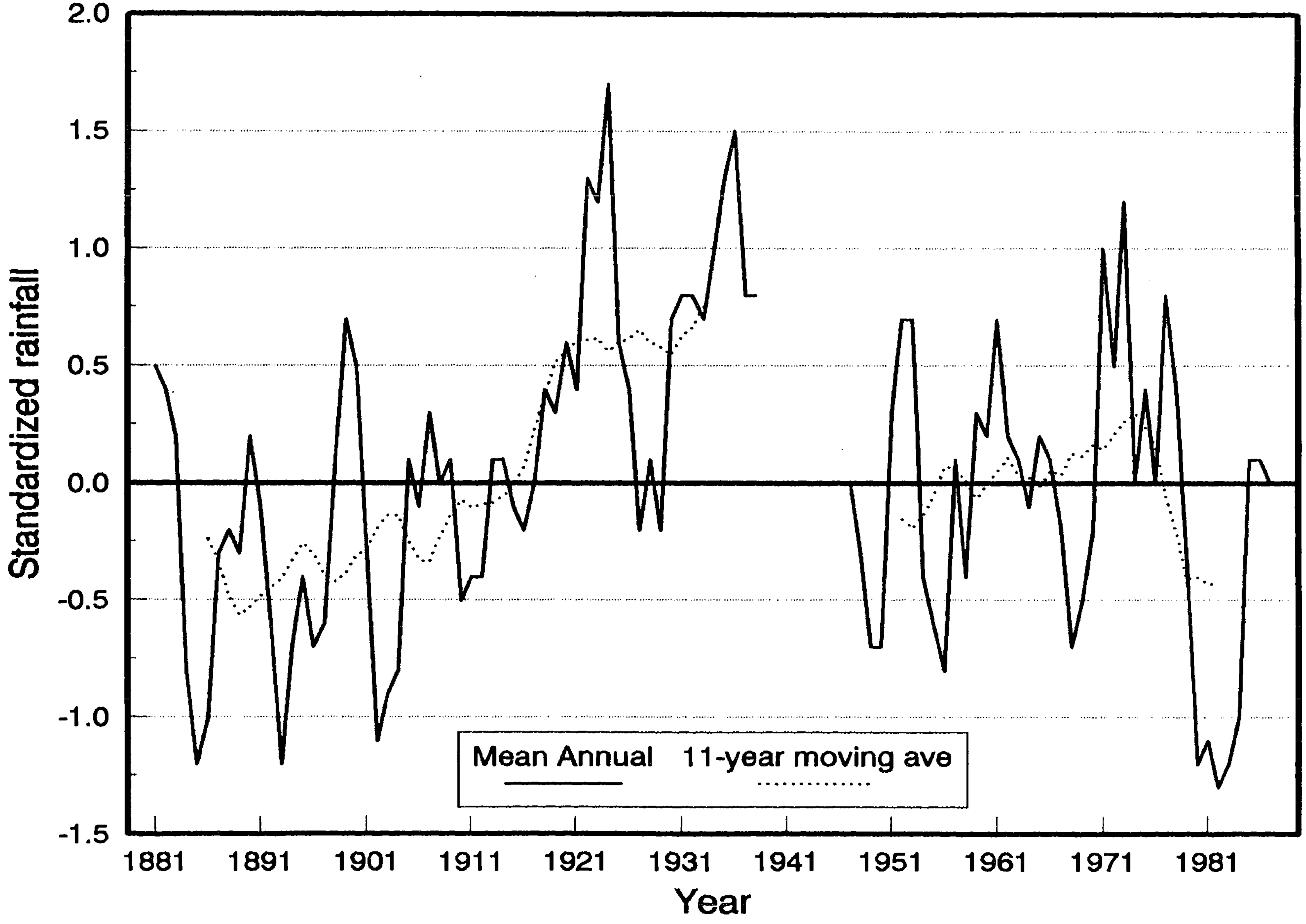
Fig. 9. Same as Fig. 5, but for NE monsoon experiments. Note change in range along abscissa.

Fig. 10. Same as Fig. 5, but for calm wind experiments.

Fig. 11. Same as Fig. 2, but for 1200 LST, calm wind experiments.


Standardized rainfall
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
1881
1891
1901
1911
1921
1931
1941
1951
1961
1971
1981
Year
Mean SW
11-year moving ave


2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
Standardized rainfall
1881
1891
1901
1911
1921
1931
1941
1951
1961
1971
1981
Year
Mean NE
11-year moving ave


Standardized rainfall
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
1881
1891
1901
1911
1921
1931
1941
1951
1961
1971
1981
Year
Mean Annual
11-year moving ave

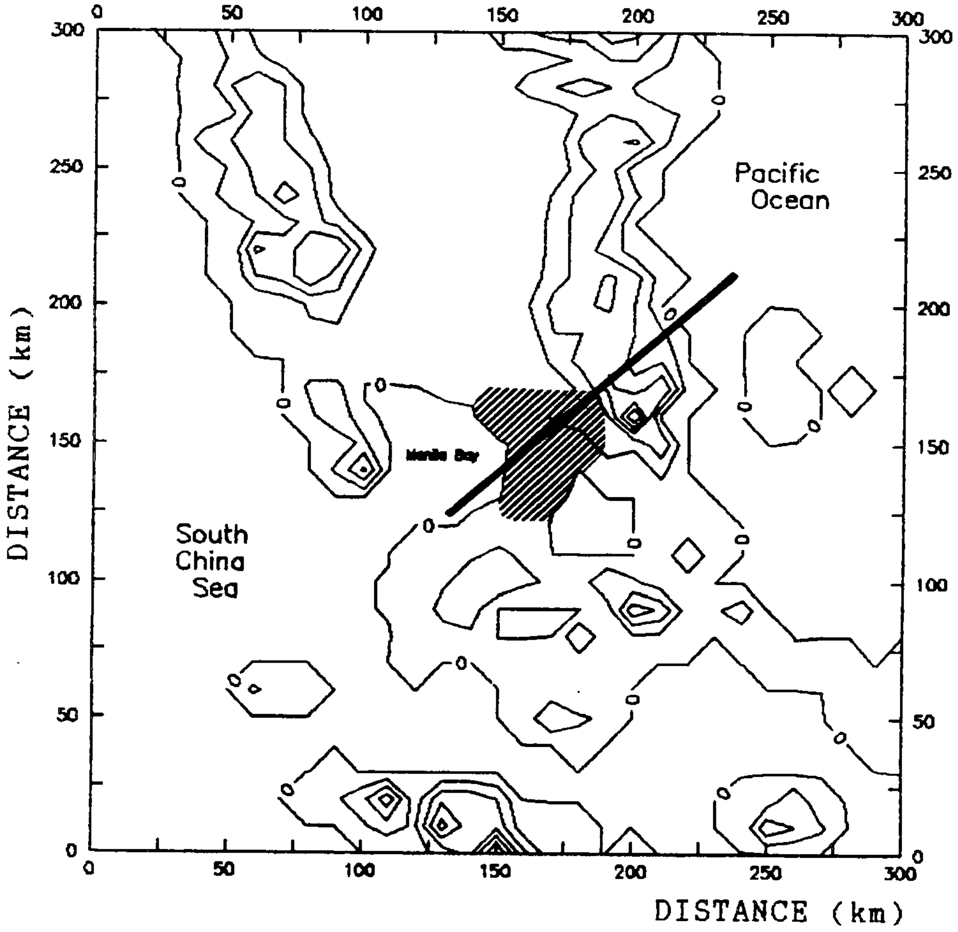
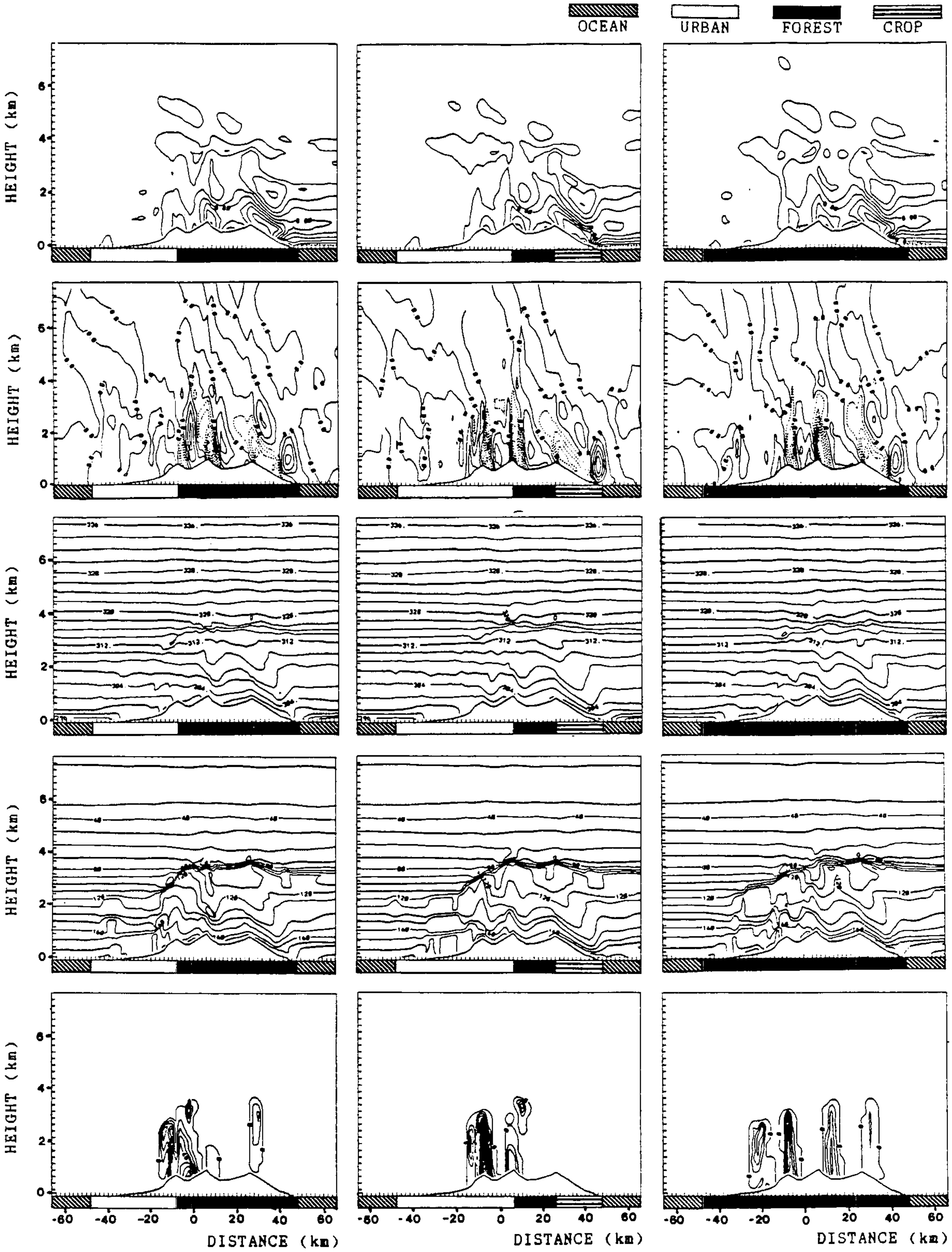
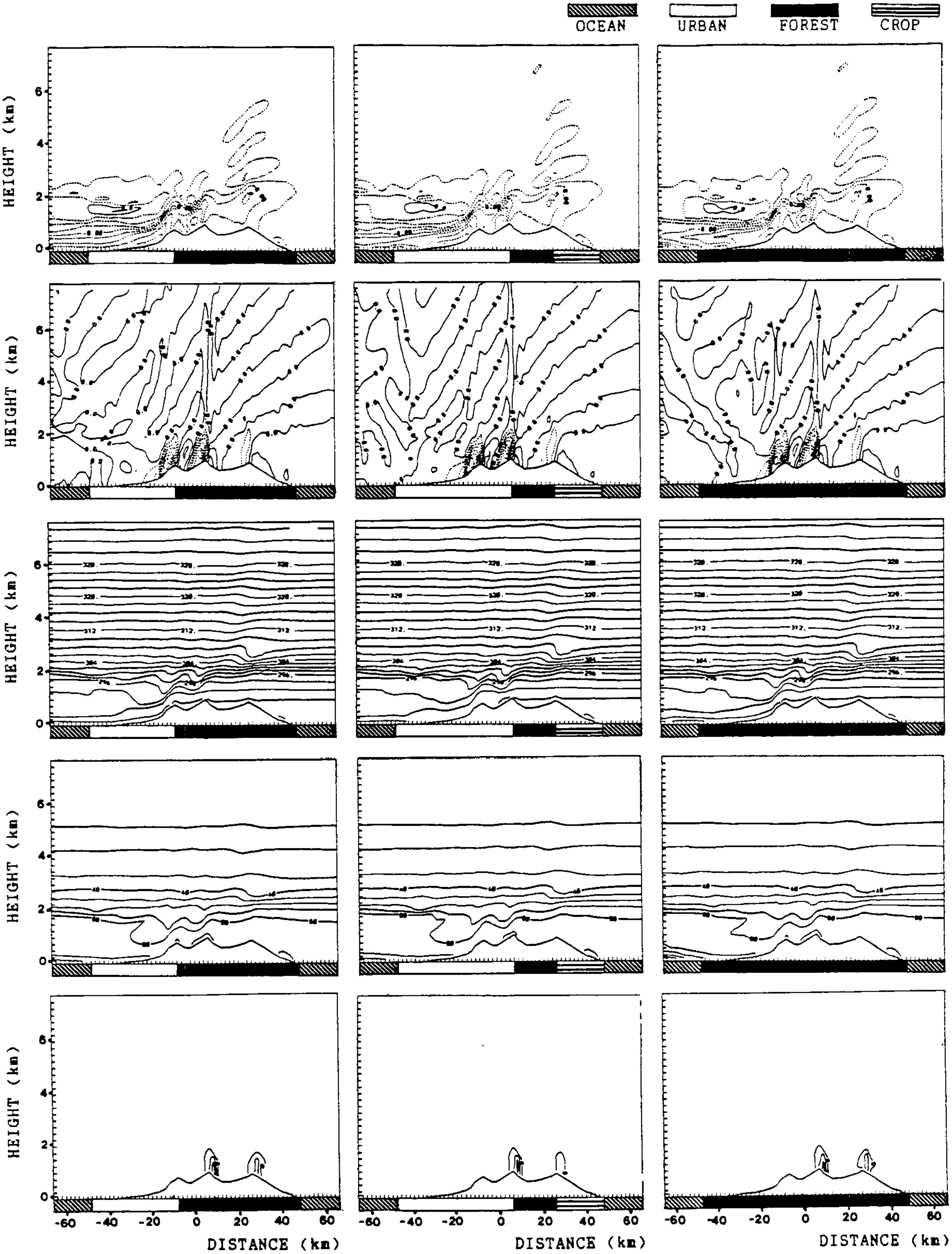

DISTANCE (km)
DISTANCE (km)
0
50
100
150
200
250
300
Pacific
Ocean
South
China
Sea
Manila Bay
0

Fig. 6


OCEAN
URBAN
FOREST
CROP
HEIGHT (km)
0
2
4
6
336
328
320
312
304
48
88
128
168
DISTANCE (km)
-60
-40
-20
0
20
40
60


OCEAN
URBAN
FOREST
CROP
HEIGHT (km)
0
2
4
6
320
328
312
304
296
48
60
-60
-40
-20
0
20
40
60
DISTANCE (km)

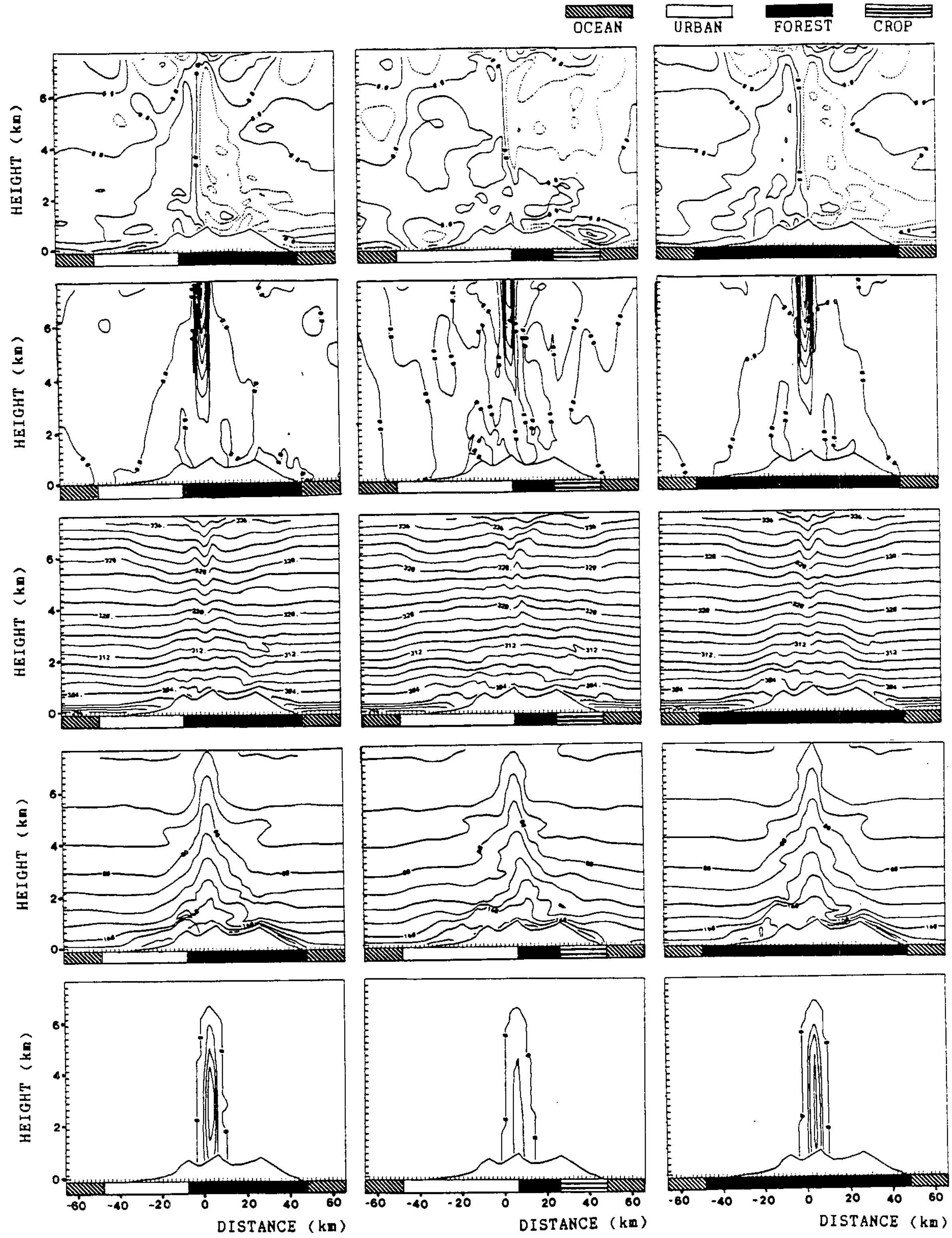

OCEAN
URBAN
FOREST
CROP
HEIGHT (km)
0
2
4
6
336
328
320
312
304
DISTANCE (km)
-60
-40
-20
0
20
40
60

Fig. 1

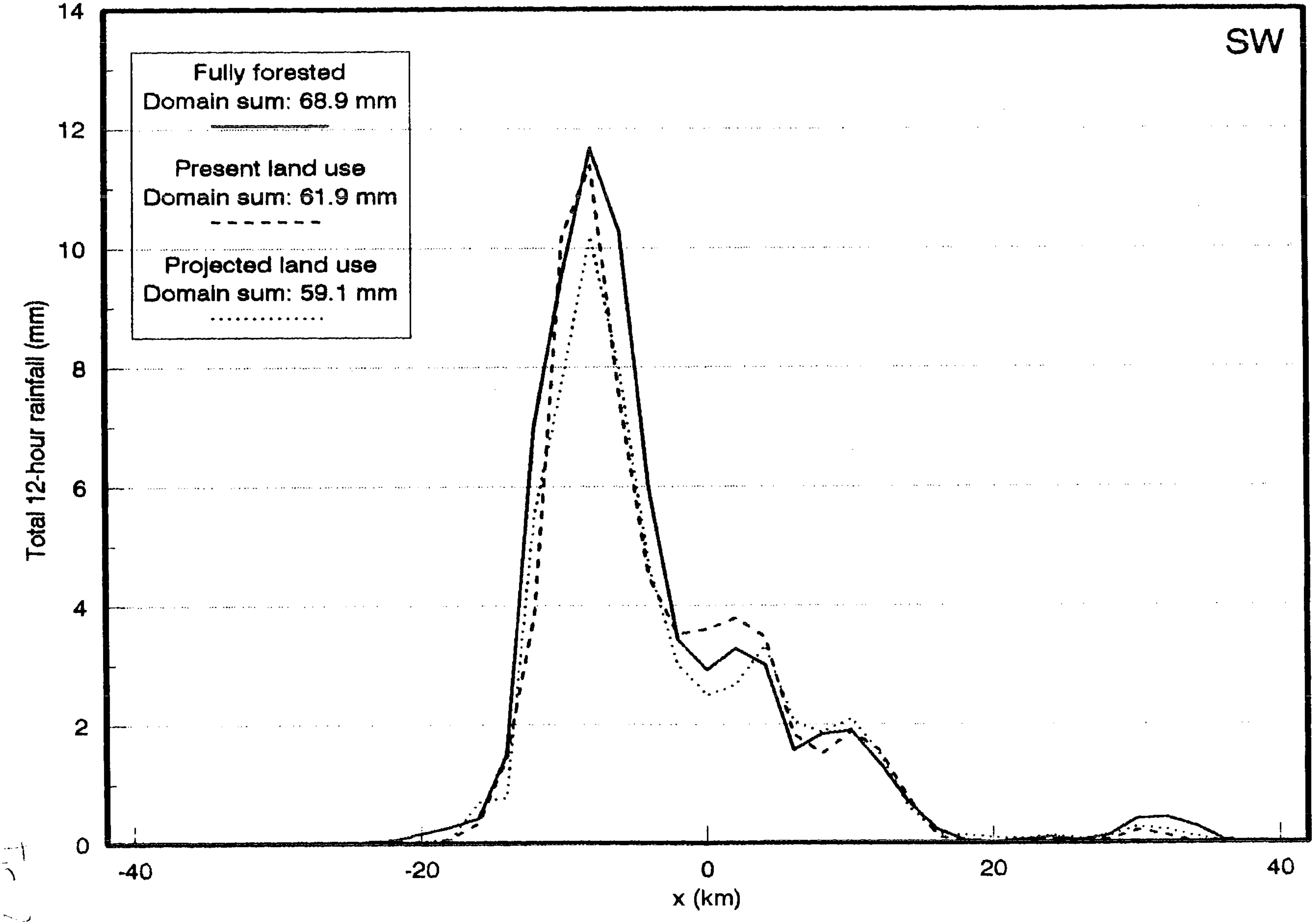
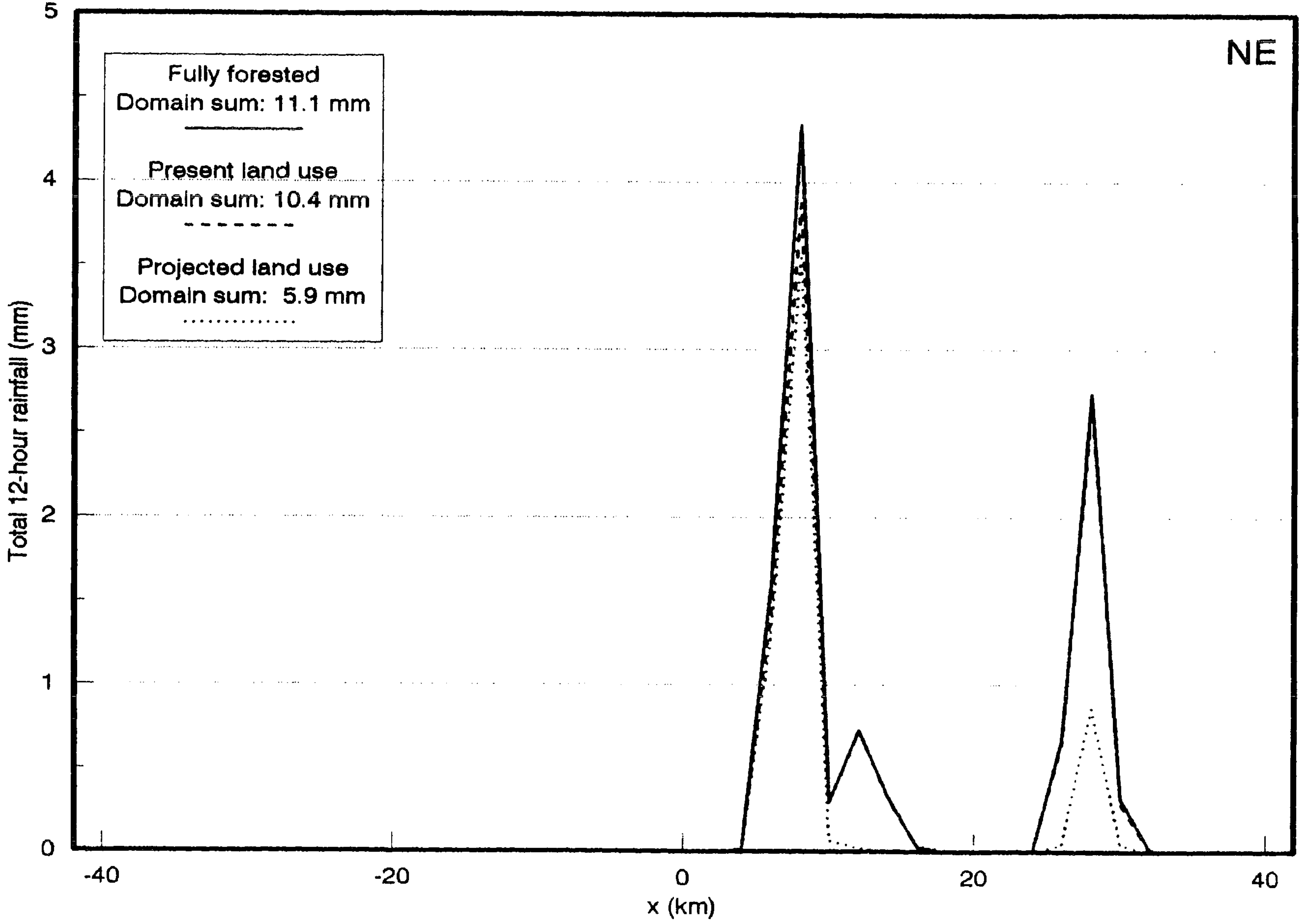
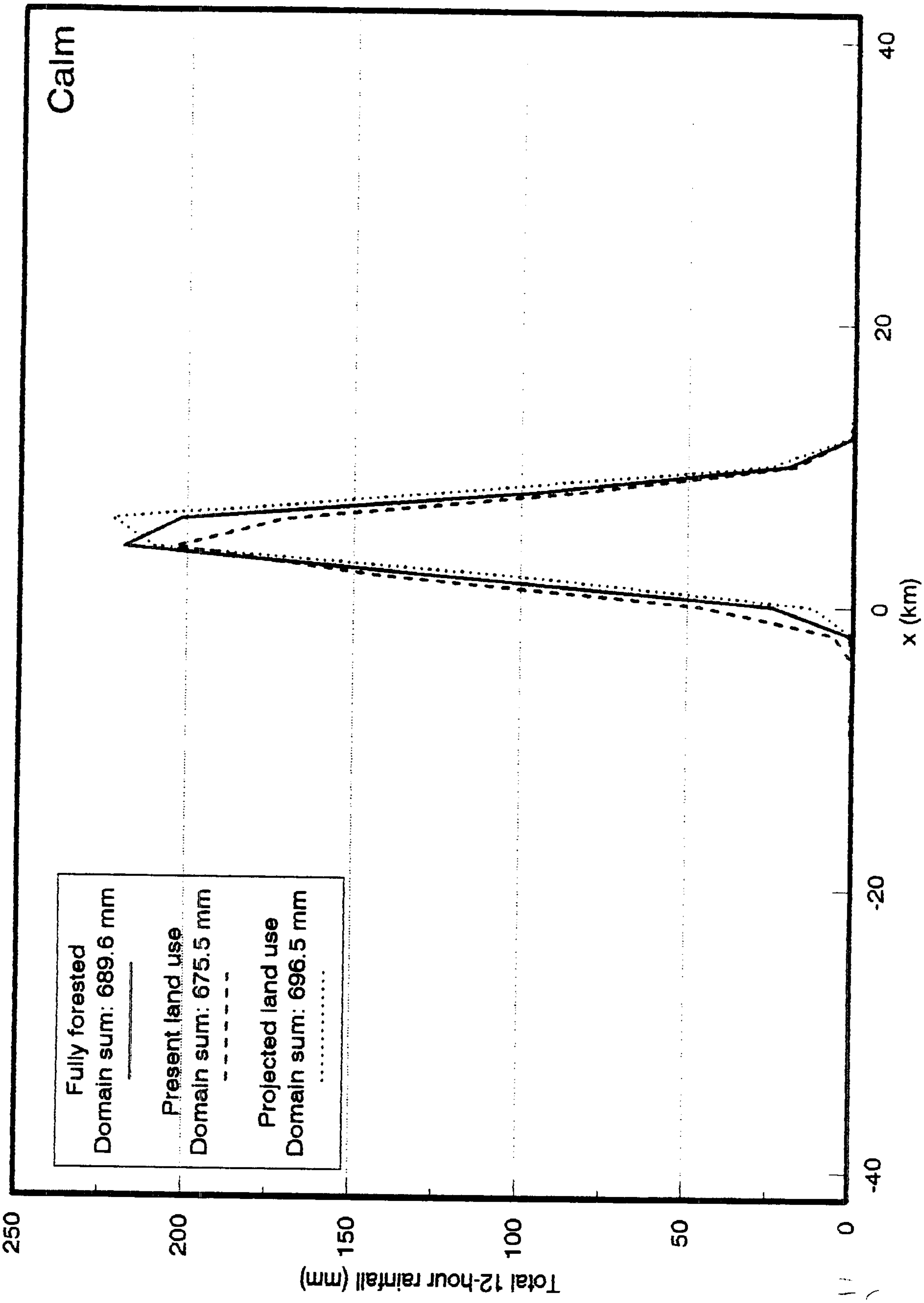
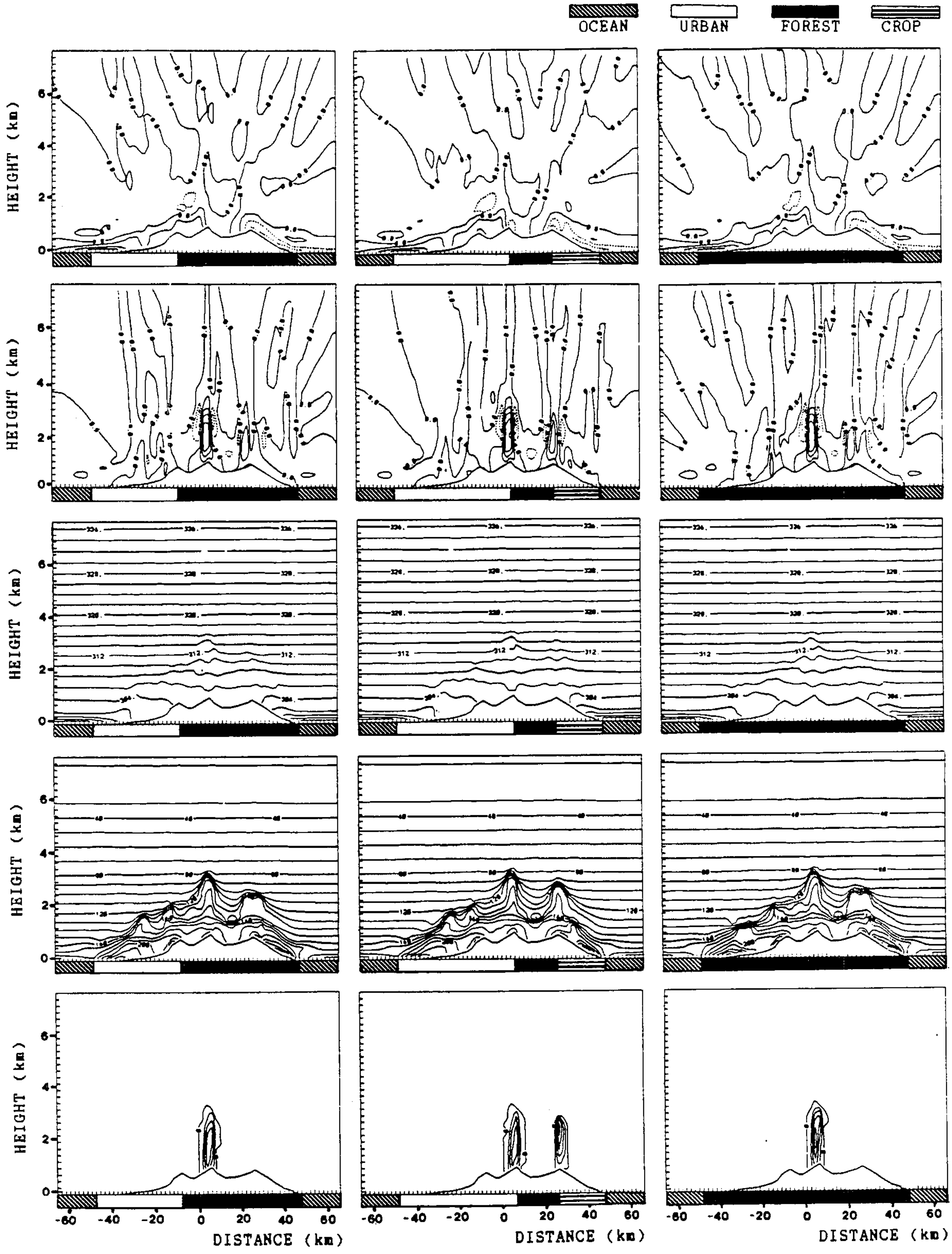

SW
Fully forested
Domain sum: 68.9 mm
Present land use
Domain sum: 61.9 mm
Projected land use
Domain sum: 59.1 mm
Total 12-hour rainfall (mm)
0
2
4
6
8
10
12
14
-40
-20
0
20
40
x (km)

Fig 2


NE
Fully forested
Domain sum: 11.1 mm
Present land use
Domain sum: 10.4 mm
Projected land use
Domain sum: 5.9 mm
Total 12-hour rainfall (mm)
0
1
2
3
4
5
-40
-20
0
20
40
x (km)


Calm
Fully forested
Domain sum: 689.6 mm
Present land use
Domain sum: 675.5 mm
Projected land use
Domain sum: 696.5 mm
Total 12-hour rainfall (mm)
0
50
100
150
200
250
x (km)
-40
-20
0
20
40


OCEAN
URBAN
FOREST
CROP
HEIGHT (km)
0
2
4
6
336.
328.
320.
312
304
48
88
128
168
208
-60
-40
-20
0
20
40
60
DISTANCE (km)

Fi 6