

















































415 Atmospheric Boundary Layer at the coastal station, GMMC, well in comparison with the  
416 observed sounding at 0000 UTC.

417 Regarding the main factors leading to fog onset and dissipation, numerical results confirm all  
418 the findings of the observational analysis with more details about the interaction between the  
419 physical processes during the whole life cycle of the studied fog event. The onset stage was  
420 governed by weak turbulence and nocturnal radiative cooling at both stations while the mature  
421 phase and dissipation phase were slightly different. In fact, over the coastal station, GMMC, a  
422 zone of moisture flux convergence at the fog layer top, in addition to the coupling between the  
423 radiative cooling at the fog top and the vertical mixing, helped to maintain the fog layer. This  
424 coupling was also the main mechanism leading to the fog thickening at the inland station,  
425 GMMN. However, the dissipation phase at GMMN was governed by a zone of moisture  
426 divergence at the top of the fog layer, linked to the advection of dry air from the south, while a  
427 similar zone was located in the bottom of the fog layer over GMMC.

428 Sensitivity experiments to surface heterogeneities demonstrated that numerical coastal fog  
429 prediction was influenced by local topography and urbanization for this case study, but less by  
430 land cover. On the other hand, sensitivity experiments to aerosols pointed out that their impact  
431 was higher near the coast. It was found that the displacement of maritime aerosols over land had  
432 little impact on the fog patch at the inland station, while the continental aerosol potentially

433 influenced the life time of fog near the coast. In fact, continental droplets are smaller than the  
434 maritime ones. This produces less gravitational settling and consequently higher liquid water  
435 content.

436 This paper was limited to the study of an interesting case of advection-radiation fog in real  
437 synoptic conditions in order to help to fill some gaps in our partial knowledge of the life cycle of  
438 advection-radiation fog over heterogeneous coastal areas. Further investigation is needed with  
439 emphasis on how fog forecasts can be improved over coastal regions, particularly over the Grand  
440 Casablanca region in Morocco.

441

## 442 REFERENCES

443

444 Baars, J.A., Witiw, M., Al-Habash, A., Ramaprasad J. (2003). Determining fog type in the Los  
445 Angeles basin using historic surface observation data. In Proc. 16<sup>th</sup> Conf. on Probability and  
446 Statistics in the Atmospheric Sciences.

447 Bari, D., Bergot, T. and EL Khlifi, M. (2016). Local meteorological and large scale weather  
448 characteristics of fog over the Grand Casablanca region, Morocco. *J. Appl. Meteor. Climatol.*  
449 55(8): 1731-1745. doi: 10.1175/JAMC-D-15-03141.1.

450 Bari, D., Bergot, T. and EL Khlifi, M. (2015). Numerical study of a coastal fog event over  
451 Casablanca, Morocco. *Q. J. R. Meteorolo. Soc.* 141: 1894-1905. doi:10.1002/qj.2494.



- 452 Bari, D. and EL Khlifi, M. (2015). LVP conditions at Mohamed V airport, Morocco: Local  
453 characteristics and prediction using neural networks. *International Journal of Basic and*  
454 *Applied Sciences*. 4(4): 354-363. doi: 10.14419/ijbas.v4i4.5044.
- 455 Bergot, T., Carrer, D., Noilhan, J. and Bougeault P. (2005). Improved Site-Specific Numerical  
456 Prediction of Fog and Low Clouds: A Feasibility Study. *Wea. Forecasting*. 20: 627-646.  
457 doi:10.1175/WAF873.1
- 458 Bergot, T., Terradellas, E., Cuxart, J., Mira, A., Liechti, O., Mueller, M., Nielsen, N.W. (2007).  
459 Intercomparison of Single-Column Numerical Models for the Prediction of Radiation Fog. *J.*  
460 *Appl. Meteor. Clim.* 46:504-521.
- 461 Bergot, T. (2013). Small-scale structure of radiation fog: a large-eddy simulation study. *Q. J. R.*  
462 *Meteorol. Soc.* 139: 1099-1112.
- 463 Bergot, T., Escobar, J. and Masson V. (2014). Effect of small scale surface heterogeneities and  
464 buildings on radiation fog : Large-Eddy Simulation study at Paris-Charles de Gaulle airport. *Q.*  
465 *J. R. Meteorol. Soc.* doi: 10.1002/qj.2358.
- 466 Bougeault, P. and Lacarrère, P. (1989). Parameterization of orography-induced turbulence in a  
467 mesobeta-scale model. *Mon. Wea. Rev.* 117:1872-1890.
- 468 Boutle, I.A., Finnenkoetter, A., Lock, A.P. and Wells, H. (2016), The London Model: forecasting  
469 fog at 333 m resolution. *Q. J. R. Meteorol. Soc.*, 142: 360–371. doi:10.1002/qj.2656

470 Cermak, J., Bendix, J. (2007). Dynamical Nighttime Fog/Low Stratus Detection Based on  
471 Meteosat SEVIRI Data: A Feasibility Study. *Pure Appl. Geophys.* 164: 1179-1192.

472 Charnock, H. (1955). Wind stress on a water surface. *Q. J. R. Meteorol. Soc.* 81: 639-640

473 Cohard, J.-M., Pinty, J.-P. and Suhre, K. (2000). On the parameterization of activation spectra  
474 from cloud condensation nuclei microphysical properties. *Journal of Geophysical Research.*  
475 105 (D9), 11753–11766.

476 Cuxart, J., Bougeault, P. and Redelsperger, J.L. (2000). A turbulence scheme allowing for  
477 mesoscale and large-eddy simulations. *Q. J. R. Meteorol. Soc.* 126: 1-30.

478 Cuxart, J. and Jiménez, M.A. (2007). Mixing processes in a nocturnal low-level jet: An LES  
479 study. *Journal of the atmospheric sciences.* 64(5): 1666-1679.

480 Cuxart, J. and Jiménez, M.A. (2012). Deep radiation fog in a wide closed valley: Study by  
481 numerical modeling and remote sensing. *Pure. Appl. Geophys.* 169:911-926.

482 Dee, D.P., Uppala, S.M., Simmons, A.J., Berrisford, P., Poli, P., Kobayashi, S., Andrae, U.,  
483 Balmaseda, M.A., Balsamo, G., Bauer, P., Bechtold, P., Beljaars, A.C.M, van de Berg, L.,  
484 Bidlot, J., Bormann, N., Delsol, C., Dragani, R., Fuentes, M., Geer, A.J., Haimberger, L.,  
485 Healy, S.B., Hersbach, H., Hólm, E.V., Isaksen, L., Källberg, P., Köhler, M., Matricardi, M.,  
486 McNally, A.P., Monge-Sanz, B.M., Morcrette, J.J., Park, B.K., Peubey, C., de Rosnay, P.,  
487 Tavolato, C., Thépaut, J.N., Vitart, F. (2011). The ERA-Interim reanalysis: configuration and

488 performance of the data assimilation system. *Q. J. R. Meteorol. Soc.* 137: 553-597.

489 Durran, D.R. (1989). Improving the anelastic approximation. *Journal of the atmospheric sciences.*  
490 46(11): 1453-1461.

491 Duynkerke, P.G. (1991). Radiation fog: A comparison of model simulation with detailed  
492 observations. *Monthly Weather Review.* 119(2): 324-341.

493 Dupont, J.C., Haeffelin, M., Protat, A., Bouniol, D., Boyouk, N. and Morille, Y. (2012). Stratus  
494 fog formation and dissipation: a 6-day case study. *Boundary-layer meteorology.* 143(1): 207-  
495 225.

496 George, J.J. (1951). Fog. *Compendium of meteorology*, 1179-1189.

497 Gheusi, F., Stein, J. (2002). Lagrangian description of airflows using Eulerian passive tracers.  
498 *Quarterly Journal of the Royal Meteorological Society.* 128(579): 337-360.

499 Gultepe, I., Tardif, R., Michaelides, S.C., Cermak, J., Bott, A., Bendix, J., Müller, M.D.,  
500 Pagowski, M., Hansen, B., Ellrod, G., Jacobs, W., Toth, G. and Cobe, S.G. (2007). Fog  
501 Research: A Review of Past Achievements and Future Perspectives. *Pure Appl. Geophys.* 164:  
502 1121-1159.

503 Hilliker, J.L. and Fritsch, J.M. (1999). An observations-based statistical system for warm-season  
504 hourly probabilistic forecasts of low ceiling at the San Francisco International Airport. *Journal*  
505 *of Applied Meteorology.* 38(12): 1692-1705.

506 Khairoutdinov, M., and Kogan, Y. (2000). A new cloud physics parameterization in a large-eddy  
507 simulation model of marine stratocumulus. *Monthly Weather Review*. 128 (1), 229–243.

508 Koracin, D., Lewis, J., Thompson, W.T., Dorman, C.E. and Businger, J.A. (2001). Transition of  
509 stratus into fog along the California Coast: Observations and modeling. *J. Atmos. Sci.* 58:  
510 1714-173

511 Lafore, J.P., Stein, J., Asencio, N., Bougeault, P., Ducrocq, V., Duron, J., Fischer, C., Hereil, P.,  
512 Mascart, P., Pinty, J.P., Redelsperger, J.L., Richard, E., De Arellano, J.V.G. (1998). The Meso-  
513 NH Atmospheric Simulation System. Part I: Adiabatic formulation and control simulations.  
514 *Ann. Geophys.* 16: 90-109.

515 Martínez, D., Jiménez, M. A., Cuxart, J. and Mahrt, L. (2010). Heterogeneous nocturnal cooling  
516 in a large basin under very stable conditions. *Boundary-layer meteorology*. 137(1): 97-113.

517 Musson-Genon, L. (1987). Numerical simulation of a fog event with a one-dimensional boundary  
518 layer model. *Monthly Weather Review*. 115(2): 592-607.

519 Masson V. (2000). A physically based scheme for the urban energy budget in atmospheric  
520 models. *Bound.-Lay. Meteorol.* 94: 357-397.

521 Masson, V., Champeaux, J.L., Chauvin, F., Meriguet, C. and Lacaze, R. (2003). A global  
522 database of land surface parameters at 1-km resolution in meteorological and climate models.  
523 *Journal of climate*. 16(9): 1261-1282.

524 Mironov, D., Golosov, S., Heise, E., Kourzeneva, E., Ritter, B., Scheider, N. and Terzhevik, A.  
525 (2005). Flake - A Lake Model for Environmental Applications. In Proceedings of the 9th  
526 Workshop on Physical Processes in Natural Waters, Lancaster University, UK, September  
527 2005, A. Folkard and I. Jones, Eds.

528 Mlawer, E.J., Taubman, S.J., Brown, P.D., Iacono, M.J., Clough, S.A. (1997). Radiative transfer  
529 for inhomogeneous atmospheres: RRTM, a validation correlated-k model for the longwave. *J.*  
530 *Geophys. Res.* 102:16663-16682.

531 Morcrette, J.J. (1991). Radiation and cloud radiative properties in the European Centre for  
532 Medium Range Weather Forecasts forecasting system. *J. Geophys. Res.* 96: 9121-9132.

533 Niu, S., Lu, C., Yu, H., Zhao, L. and Lü, J. (2010). Fog research in China: an overview. *Adv.*  
534 *Atmos. Sci.* 27: 639-662.

535 Noilhan, J., Mahfouf, J.F. (1996). The ISBA land surface parameterization scheme. *Global*  
536 *Planet. Change.* 13: 145-159.

537 Petterssen, S. (1939). Some aspects of formation and dissipation of fog. *Geophys. Publ.* 12, 522.

538 Philip, A., Bergot, T., Bouteloup, Y. and Bouysse, F. (2016). The Impact of Vertical Resolution  
539 on Fog Forecasting in the Kilometric-Scale Model AROME: A Case Study and Statistics. *Wea.*  
540 *Forecasting.* 31: 1655-1671. DOI: 10.1175/WAF-D-16-0074.1.

541 Pinty, J.P. and Jabouille, P. (1998). A mixed-phase cloud parameterization for use in mesoscale

542 non-hydrostatic model: simulations of a squall line and of orographic precipitations. In  
543 Proceedings Conf. of Cloud Physics, Everett, WA, USA, Amer. Meteor. Soc.  
544 Press, W.H., Teukolsky, S.A., Vetterling, W.T. and Flannery, B.P. (1992). Numerical Recipes in  
545 FORTRAN: The Art of Scientific Computing. 2nd ed., 963 pp, Univ. Press, Cambridge, New  
546 York.

547 Ryznar, E. (1977). Advection-radiation fog near Lake Michigan. *Atmospheric Environment*.  
548 11(5): 427-430.

549 Roquelaure, S., Tardif, R., Remy, S. and Bergot T. (2009). Skill of a Ceiling and Visibility Local  
550 Ensemble Prediction System (LEPS) according to Fog-Type Prediction at Paris-Charles de  
551 Gaulle Airport. *Wea. Forecasting*. 24: 1511-1523. doi: 10.1175/2009WAF2222213.1

552 Román-Cascón, C., Steeneveld, G. J., Yagüe, C., Sastre, M., Arrillaga, J. A. and Maqueda, G.  
553 (2016). Forecasting radiation fog at climatologically contrasting sites: evaluation of statistical  
554 methods and WRF. *Q. J. R. Meteorol. Soc.* 142: 1048–1063. doi:10.1002/qj.2708

555 Sandu, I., Brenguier, J.L., Geoffroy, O., Thouron, O., Masson, V. (2008). Aerosol impacts on the  
556 diurnal cycle of marine stratocumulus. *J. Atmos. Sci.* 65: 2705-2718.

557 Tardif, R. (2007). The impact of vertical resolution in the explicit numerical forecasting of  
558 radiation Fog: A Case Study. *Pure Appl. Geophys.* 164: 1221-1240.

559 Tardif, R., and Rasmussen, R.M. (2007). Event-based climatology and typology of fog in the

560 New York City region. *J. Appl. Meteor. Clim.* 46:1141-1168.

561 Tardif, R., and Rasmussen, R. M. (2008). Process-oriented analysis of environmental conditions  
562 associated with precipitation fog events in the New York City region. *Journal of Applied*  
563 *Meteorology and Climatology*, 47(6), 1681-1703.

564 Taylor, G.I. (1917). The formation of fog and mist. *Q. J. R. Meteorol. Soc.*, 43: 241-268. doi:  
565 10.1002/qj.49704318302

566 Ye, X., Wu, B. and Zhang, H. (2015). The turbulent structure and transport in fog layers observed  
567 over the Tianjin area. *Atmospheric Research*. 153: 217-234.

568 WMO. (1992). International meteorological vocabulary. WMO Publication 182. World  
569 Meteorological Organization: Geneva, Switzerland

570

571

572 **Table 1.** Summary of the setup of the run

Features	Details
Domains	2, one-way nested
Outer domain	500 km x 500 km (100x100 grid points)
Inner domain	100 km x 100 km (100x100 grid points)
Horizontal Resolution	5 km (outer domain), 1 km (inner domain)
Vertical resolution	60 levels, first level at 2m, 4 levels below 10m, 18 levels below 100m and 39 levels in the lowest 1000m
Time step	15s (outer domain), 5s (inner domain)
Equation system	Non-hydrostatic primitive equation of Durran (1989)
Lateral boundary conditions	Analysis from the ECMWF every 6 hours (Dee et al. (2011))
Microphysics scheme	1-moment mixed scheme (Pinty and Jabouille (1998)) Sedimentation of droplets is allowed (Bergot et al. (2007))
Radiation scheme	Long-wave radiation Mlawer et al. (1997) Short-wave radiation Morcrette (1991)
Turbulence Scheme	1-Dimensional TKE scheme Cuxart et al. (2000) Mixing length Bougeault and Lacarrère (1989)
Soil Scheme	Interaction between Soil, Biosphere and Atmosphere (Noilhan and Mahfouf (1996)) Fluxes over marine surfaces Charnock (1955) Urban and artificial areas Masson (2000)
Surface features	Land cover : ECOCLIMAP, global map, 1km resolution, Masson et al. (2003) Orography: GTOPO30, global map, 1km resolution Sand and clay fractions : FAO, 1988, global map, 10km resolution

573



574 **Table 2.** Summary of the sensitivity experiments

Experiments	Microphysical Parameterization	Details
KHKOC	Two-moment	Continental aerosols
KHKOM	Two-moment	Maritime aerosols
NORELIEF	Single-moment	The orography is removed
BARESOIL	Single-moment	Land cover is supposed uniform bare soil
URBAN	Single-moment	Land cover is supposed uniform urban where buildings fraction is 30%, and building height is 10 m

575

ACCEPTED MANUSCRIPT

576 **Table 3.** Onset and dissipation times from the control and sensitivity experiments.  
 577 Uncertainty in hours between each sensitivity experiment and the control one is shown in  
 578 parentheses.

Experiments	The coastal station GMMC		The inland station GMMC	
	Onset	Dissipation	Onset	Dissipation
REFEXP	2100UTC	0300UTC	2000UTC	0200UTC
NORELIEF	2200UTC (+1h)	After 0600UTC	2000 UTC (+0h)	After 0600 UTC
BARESOIL	2000UTC (-1h)	0200UTC (-1h)	2100 UTC (+1h)	0000 UTC (-2h)
URBAN	0000UTC (+3h)	0400UTC (+1h)	0000 UTC (+4h)	0200 UTC (+0h)
KHKOM	1900UTC (-2h)	0200UTC (-1h)	2000 UTC (+0h)	0000 UTC (-2h)
KHKOC	1900UTC (-2h)	0300UTC (+0h)	2000 UTC (+0h)	0000 UTC (-2h)

579

ACCEPTED MANUSCRIPT

580

581 **Figure Captions**

582 **Fig. 1.** (a) Map showing the land cover of the GCB region, with the locations of the two synoptic  
583 stations used in this study, (b) Map showing the topographical (m) and physiographic features of  
584 the region of interest.

585

586 **Fig. 2.** Mean sea level pressure spatial distribution at (a) 1200UTC on 23 December, (b) at  
587 1800UTC on 23 December, and (c) at 0600UTC on 24 December. The gray square refers to the  
588 GCB region. The empty square refers to a domain that will be used in the numerical simulation.

589

590 **Fig. 3.** Time series of conventional meteorological parameters: (top to bottom) cloud height base  
591 (m a.g.l), horizontal visibility (km), 10m wind direction ( $1/10^\circ$ ), 10m wind speed ( $\text{m s}^{-1}$ ) and 2m  
592 temperature ( $^\circ\text{C}$ ), for GMMC (dashed line) and GMMN (solid line) over the period from  
593 0000UTC on 23 December to 1200UTC on 24 December. The vertical bars refer to the observed  
594 onset and dissipation times of the fog event at GMMC (dashed line) and GMMN (solid line). The  
595 horizontal lines in the visibility plot refer to the fog (1km, long-dashed line) and mist (5km, dot-  
596 dashed line) thresholds. Sunrise and sunset times are shown.

597

598 **Fig. 4.** MSG derived image, following Cermak and Bendix's (2007) approach, during: (a) the  
599 formation (2100UTC on 23 Dec 2013), (b) the mature (0000UTC on 24 Dec 2013) and (c) the  
600 dissipation (0600UTC on 24 Dec 2013) phases. Square refers to MNH1.

601

602 **Fig. 5.** The liquid water path in the lowest kilometer (1-km LWP) from MNH5 (left) and MNH1  
603 (middle), and liquid water content at 2m from MNH1 (right) during: formation phase (2100UTC,  
604 top row) and dissipation phase (0600UTC, bottom row). Filled triangle and square refer to  
605 GMMN and GMMC respectively. Square in MNH5 refers to MNH1.

606

607 **Fig. 6.** (a) Time series of the 1-km resolution model simulated 2-m temperature ( $^\circ\text{C}$ ), wind speed  
608 ( $\text{m s}^{-1}$ ), wind direction ( $^\circ$ ), and 2-m relative humidity (%) at the coastal station GMMC (circles,  
609 dashed line) and at the inland station GMMN (triangles, solid line). Simulated SST (stars) is  
610 superimposed on temperatures plot. The period covers from 1200 UTC on 23 December to 0600  
611 UTC on 24 December. The vertical bars refer to the onset and dissipation times of the simulated  
612 fog event at GMMC (dashed line) and GMMN (solid line). (b) Simulated sounding superimposed  
613 on observed sounding at 0000 UTC on 24 December 2013 at the coastal station GMMC:  
614 temperature (circle for observation and solid line with x for simulation) and dew-point  
615 temperature (+ for observation and dashed line with \* for simulation).

616

617 **Fig. 7.** (a) The 9 h back trajectories of air parcels ending at GMMC and GMMN, on 23  
618 December 2013 at 2100 UTC, at the heights above ground level of 2 m (solid line), 10 m (dashed  
619 line) and 50 m (dotted line). (b) Time series of simulated water vapor mixing ratio ( $\text{g kg}^{-1}$ ), air  
620 temperature ( $^{\circ}\text{C}$ ) superimposed on dew point temperature ( $^{\circ}\text{C}$ ) and height (m a.s.l) along the  
621 back-trajectory with ending point at 2 m at GMMC (solid line with star) located at 60 m a.s.l and  
622 GMMN (dashed line with circle) located at 200 m a.s.l on 23 December at 2100 UTC. The  
623 vertical line corresponds to the time when the parcel reached the continental part of the coastal  
624 region (dashed line for GMMN and solid line for GMMC).

625

626 **Fig. 8.** Time-height contour plots of (a) and (d) simulated horizontal moisture flux divergence  
627 ( $10^{-5} \text{ g kg}^{-1} \text{ s}^{-1}$ ), (b) and (e) simulated radiative cooling ( $10^{-3} \text{ K s}^{-1}$ ) and (c) and (f) turbulent  
628 kinetic energy ( $\text{m}^2 \text{ s}^{-2}$ ) at inland station GMMN (top) and coastal station GMMC (bottom).

629

630 **Fig. 9.** Time-height contour plots of simulated LWC ( $\text{g kg}^{-1}$ ), from REFEXP and sensitivity  
631 experiments (NORELIEF, BARESOIL, URBAN, KHKOM and KHKOC) at the inland station  
632 GMMN.

633

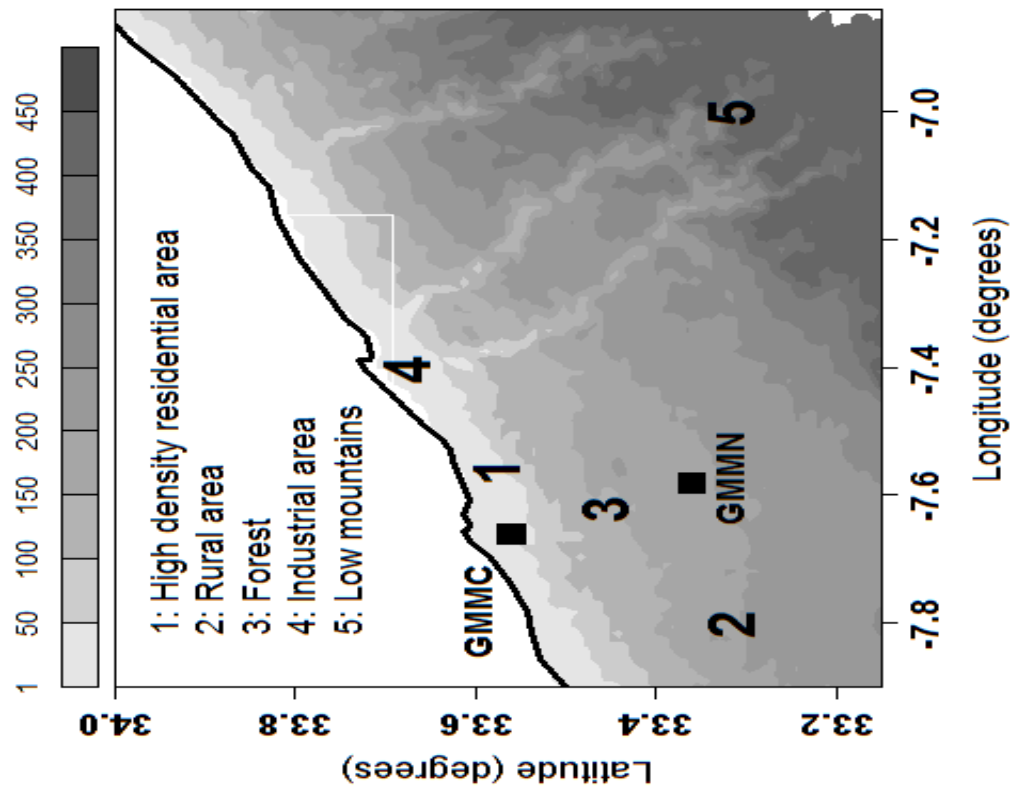
634 **Fig. 10.** Time-height contour plots of simulated LWC ( $\text{g kg}^{-1}$ ), from REFEXP and sensitivity  
635 experiments (NORELIEF, BARESOIL, URBAN, KHKOM and KHKOC) at the coastal station  
636 GMMC.

637

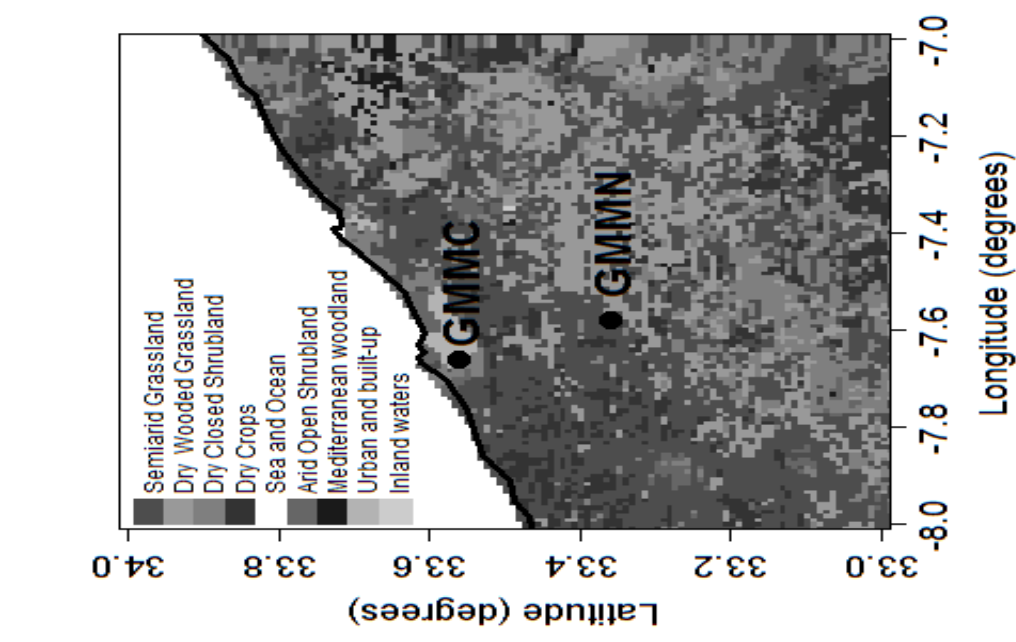
638 **Fig. 11.** The simulated 10 m wind superimposed on liquid water content at 2 m ( $\text{g kg}^{-1}$ ) from  
639 MNH5 during the mature phase (24 Dec 2013 at 0000 UTC), issued from REFEXP and  
640 sensitivity experiments (NORELIEF, BARESOIL, URBAN, KHKOM and KHKOC). Filled  
641 triangle and square indicate locations of GMMN and GMMC, respectively. Square refers to  
642 MNH1.

643

644



(a)



(b)

645  
646  
647

Fig. 1.

ACCEPTED

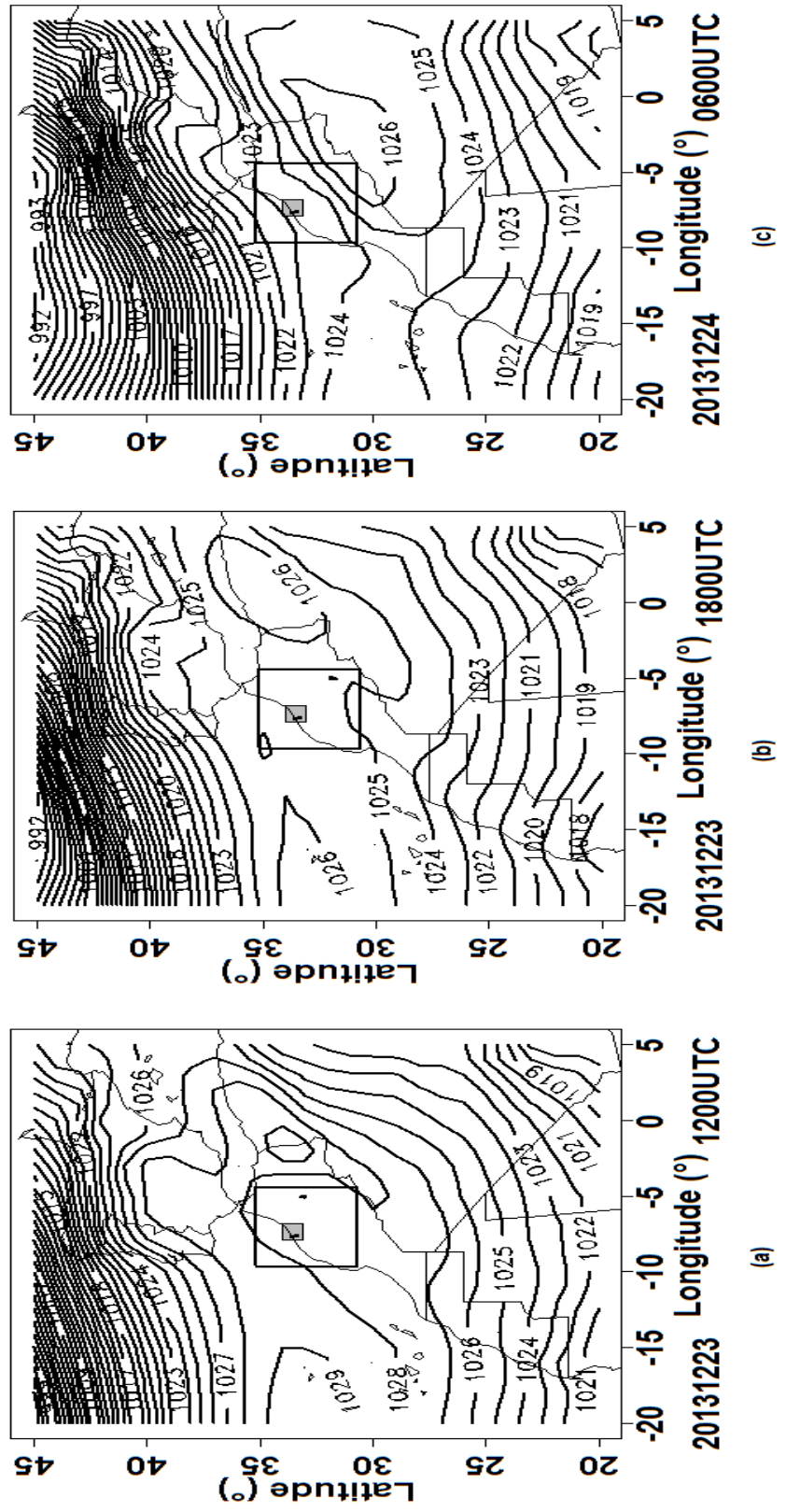


Fig. 2.

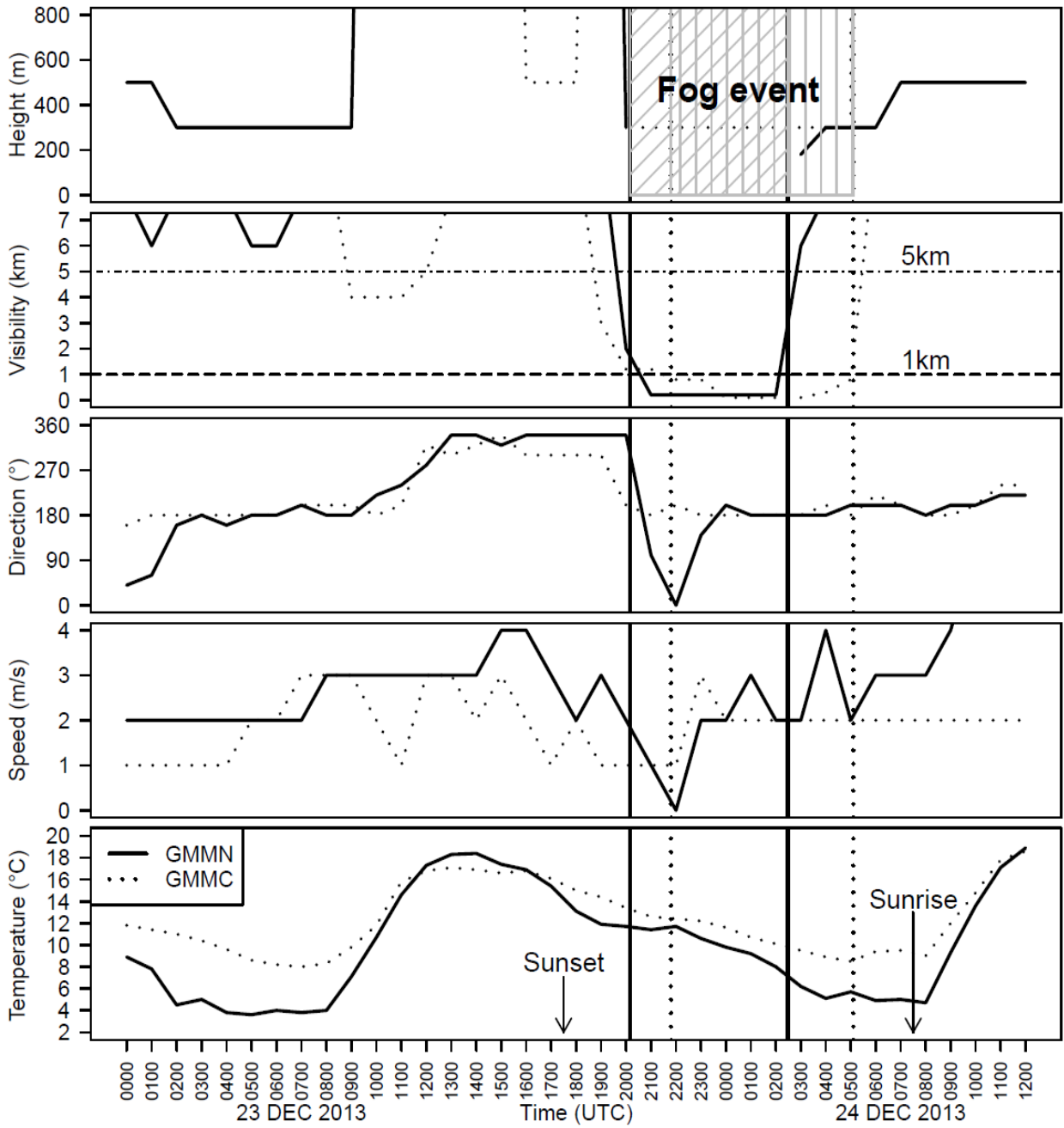
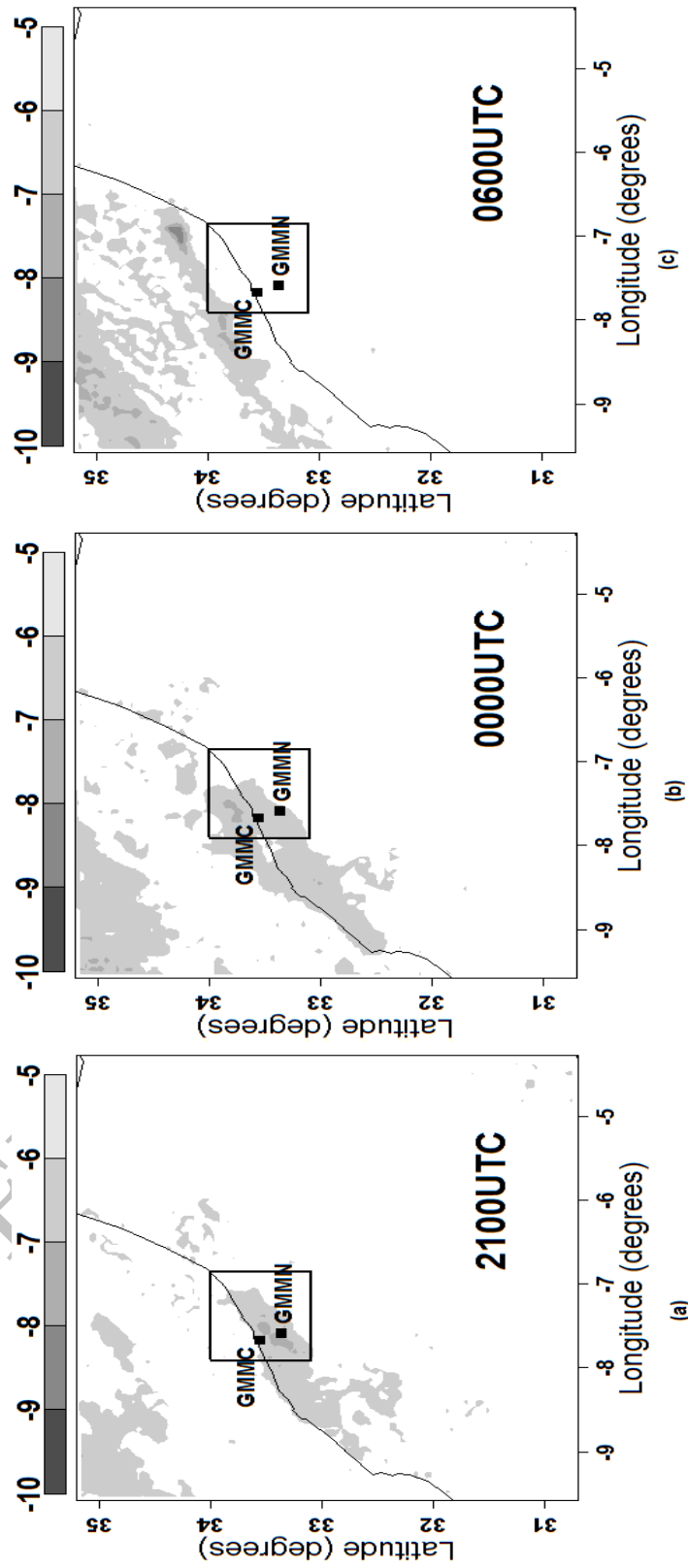


Fig. 3.

ACCEPTED



SCRIPT

654

655

Fig. 4.



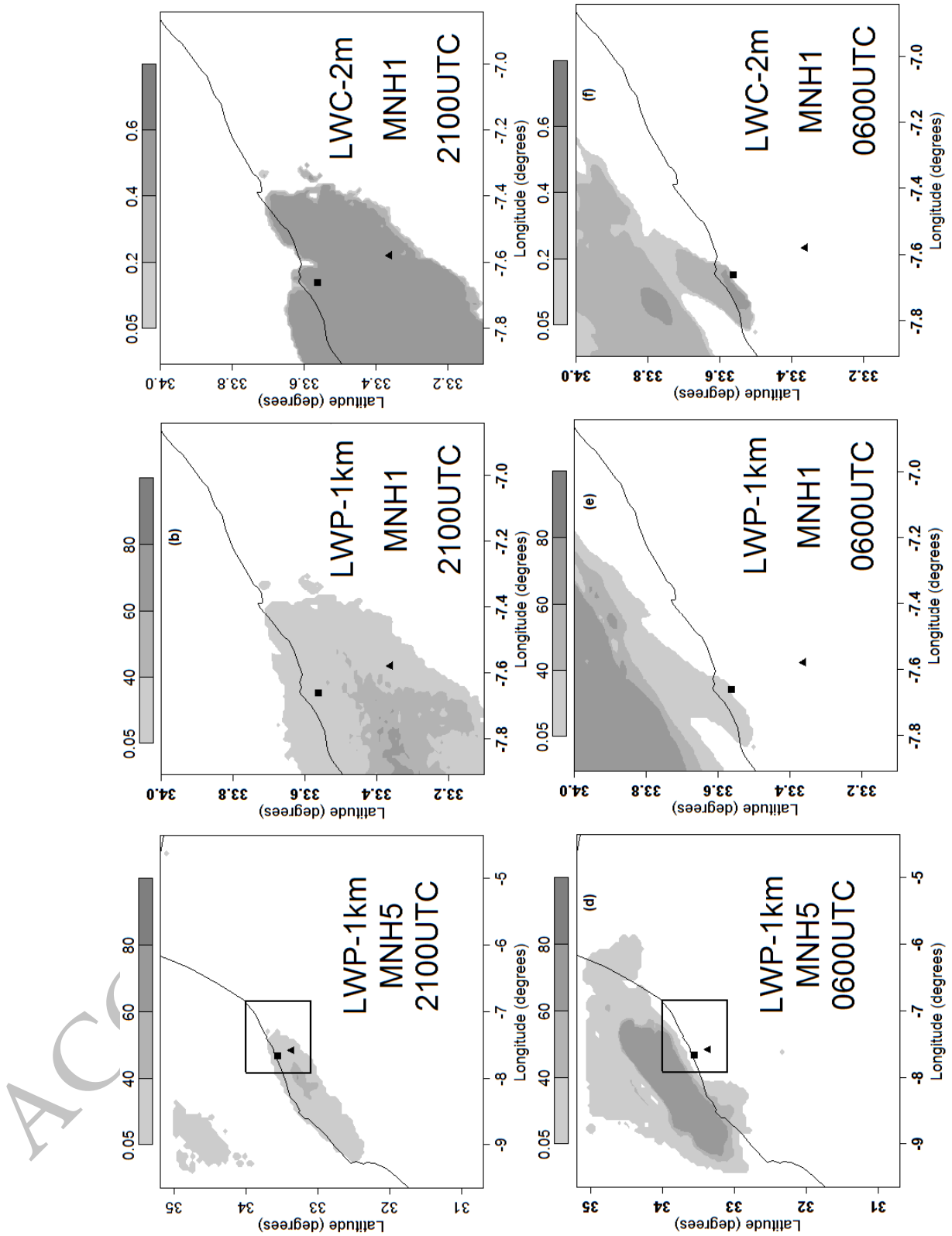
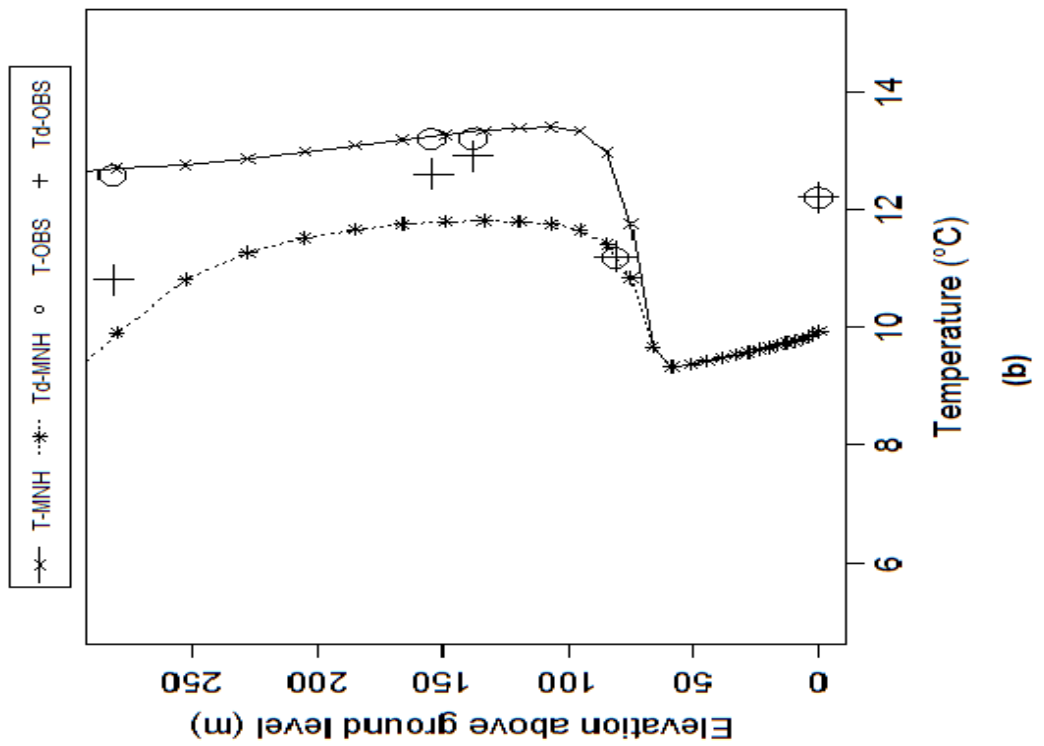
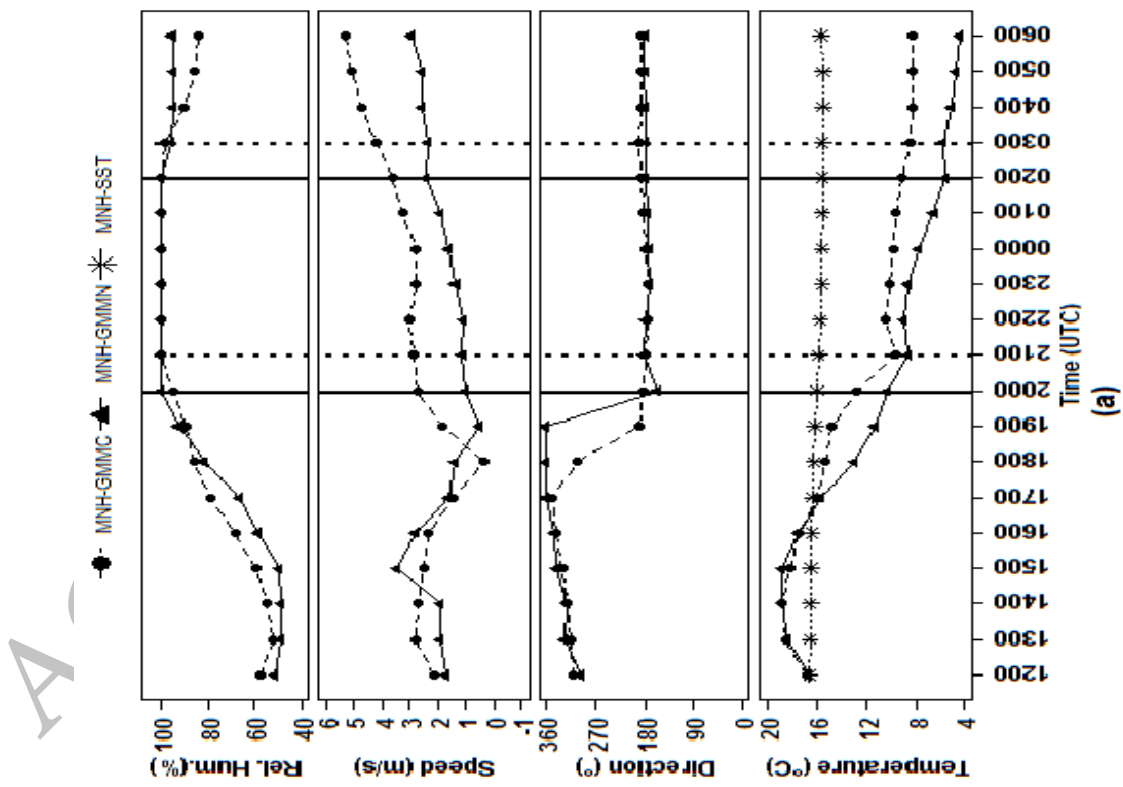


Fig. 5.

656

657

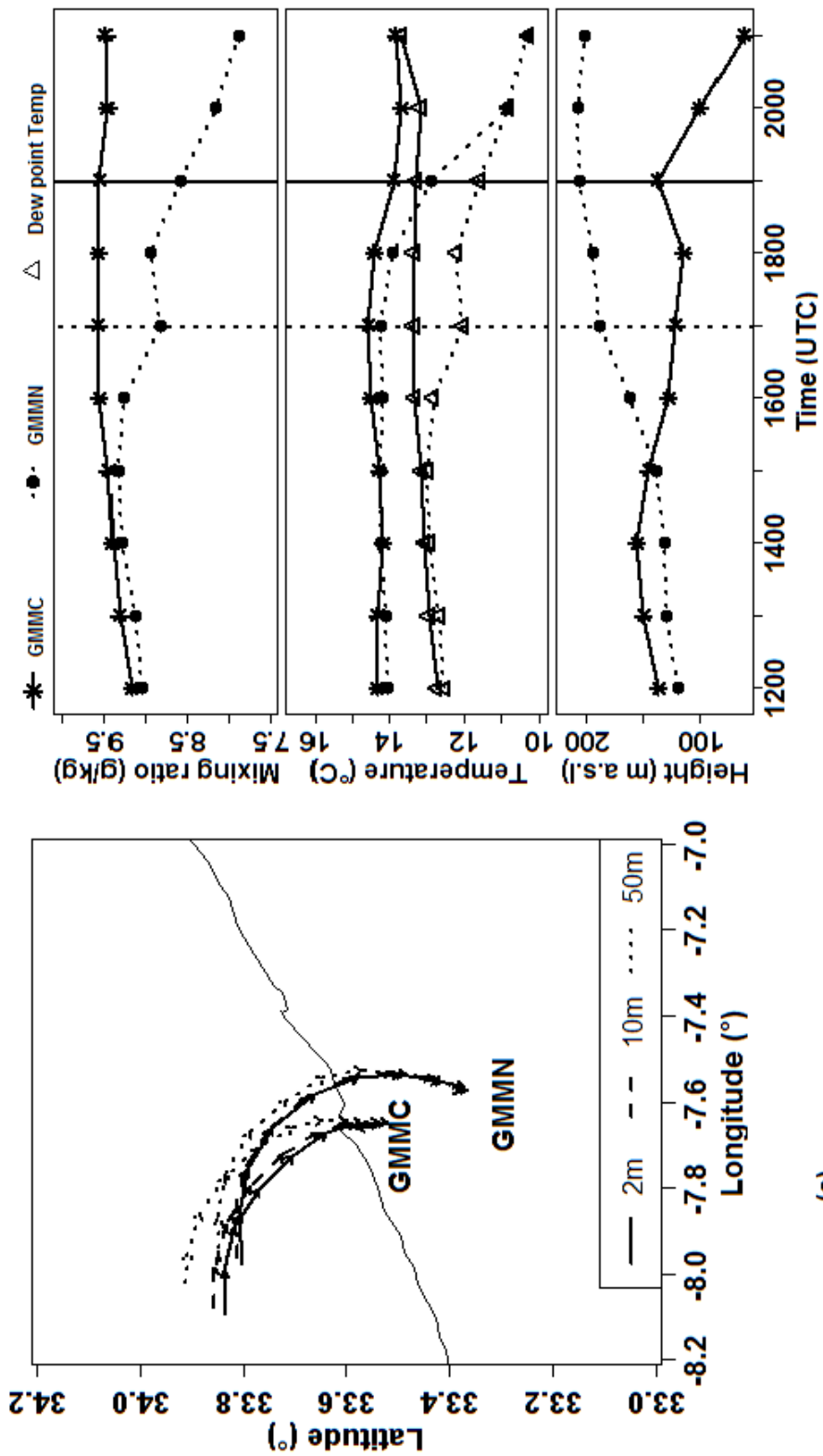


658

659

660

Fig. 6.



(a)

(b)

661

662

Fig. 7.

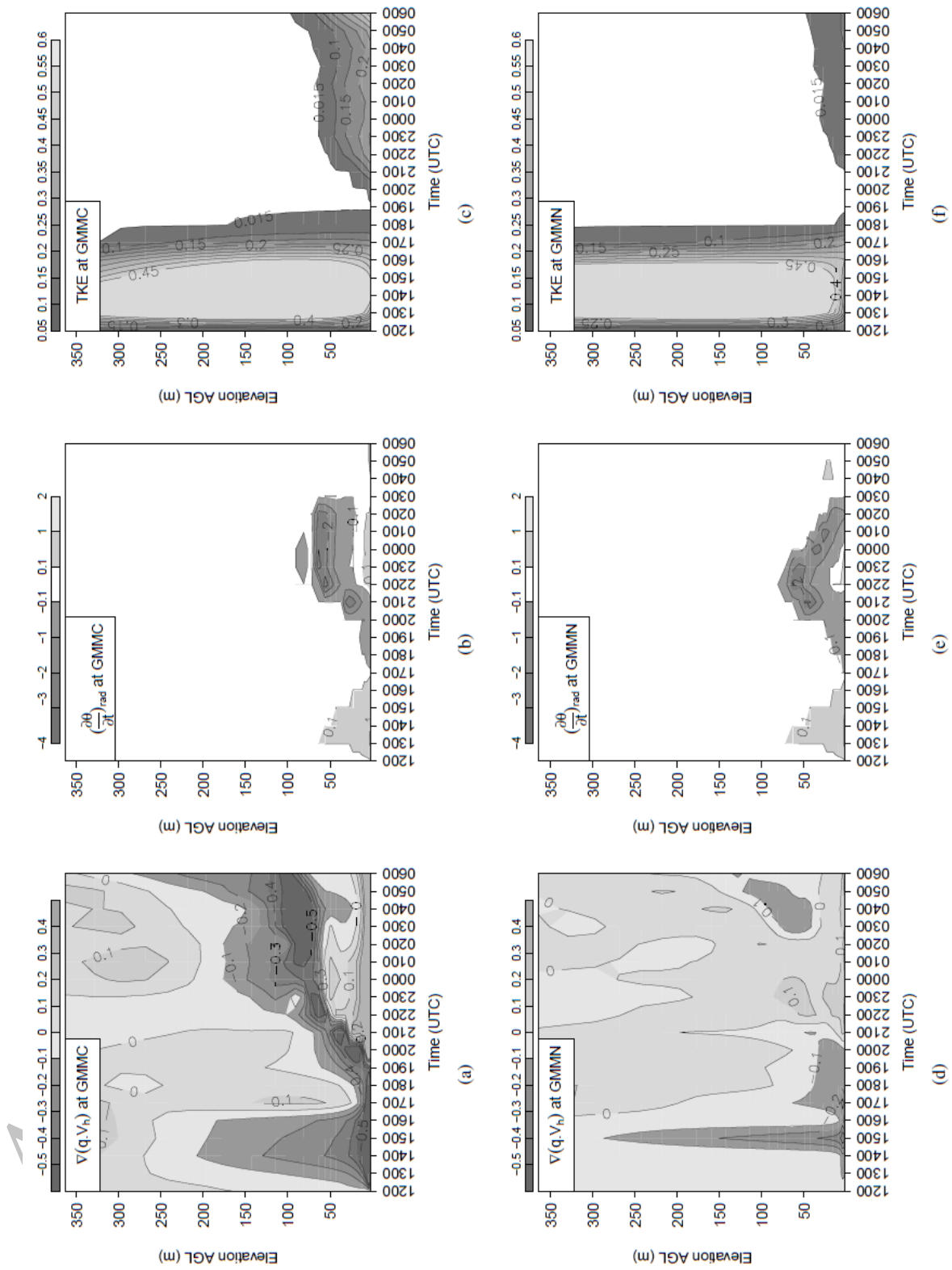


Fig. 8.

663

694

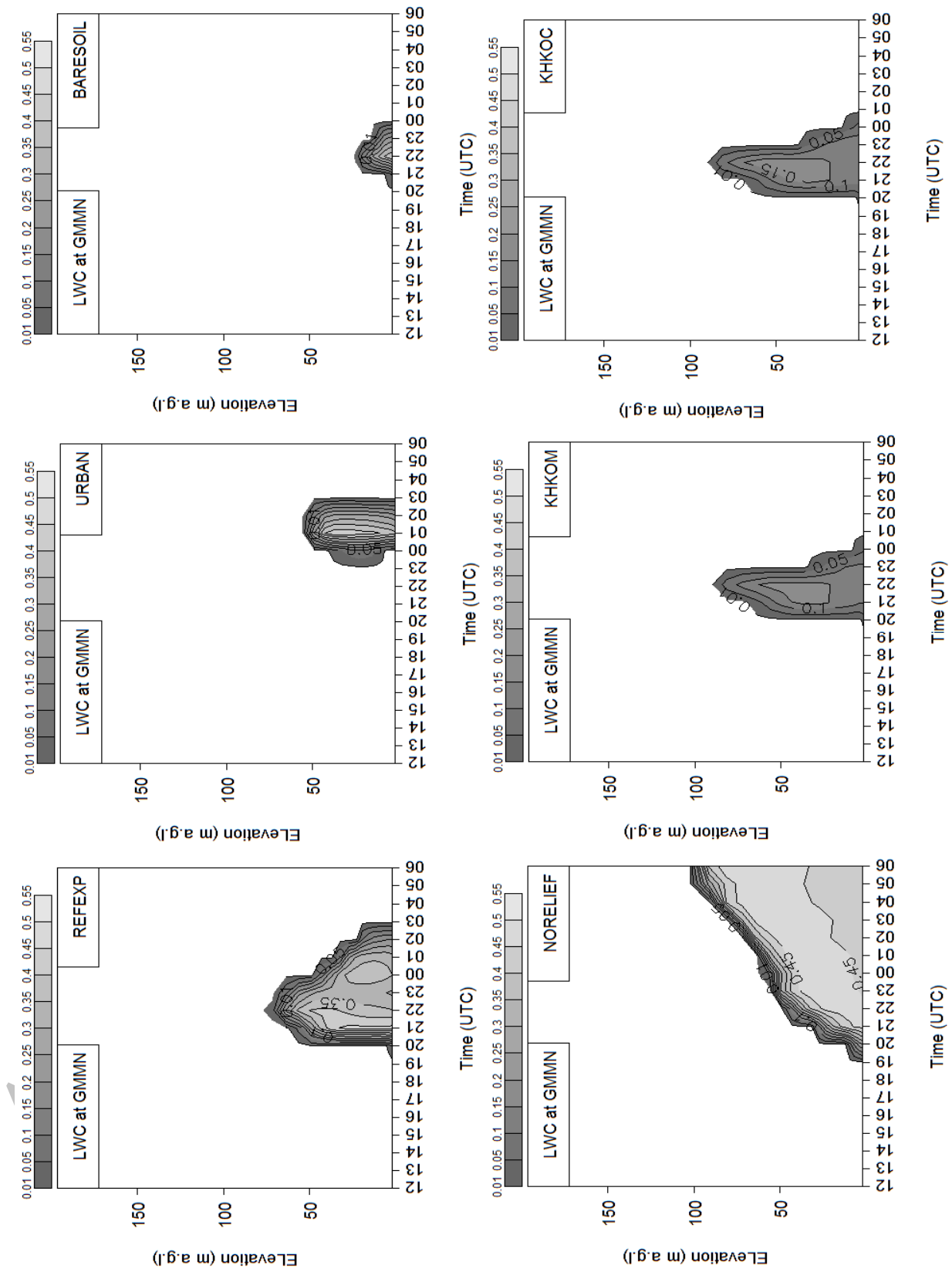


Fig. 9.

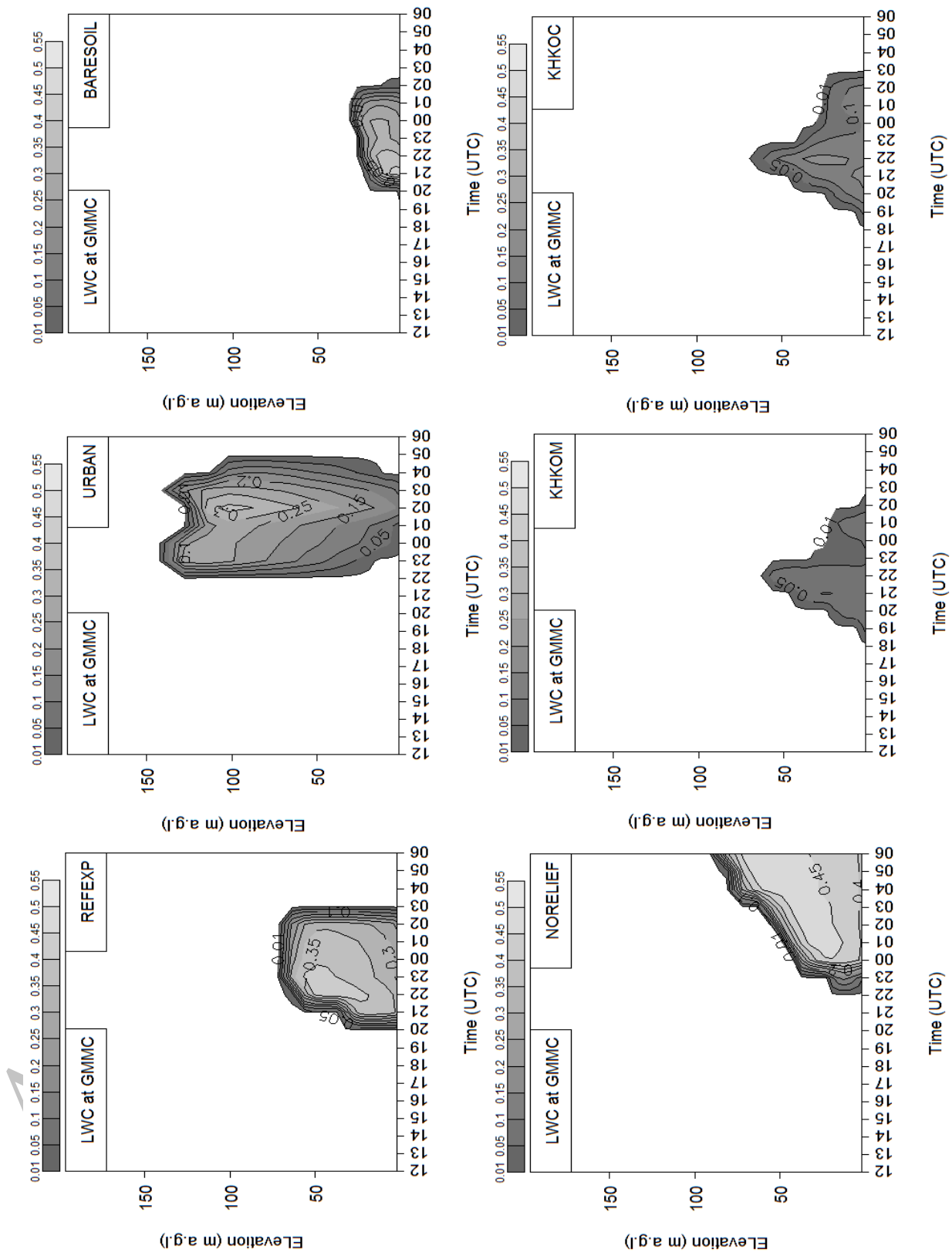


Fig. 10.

667

689

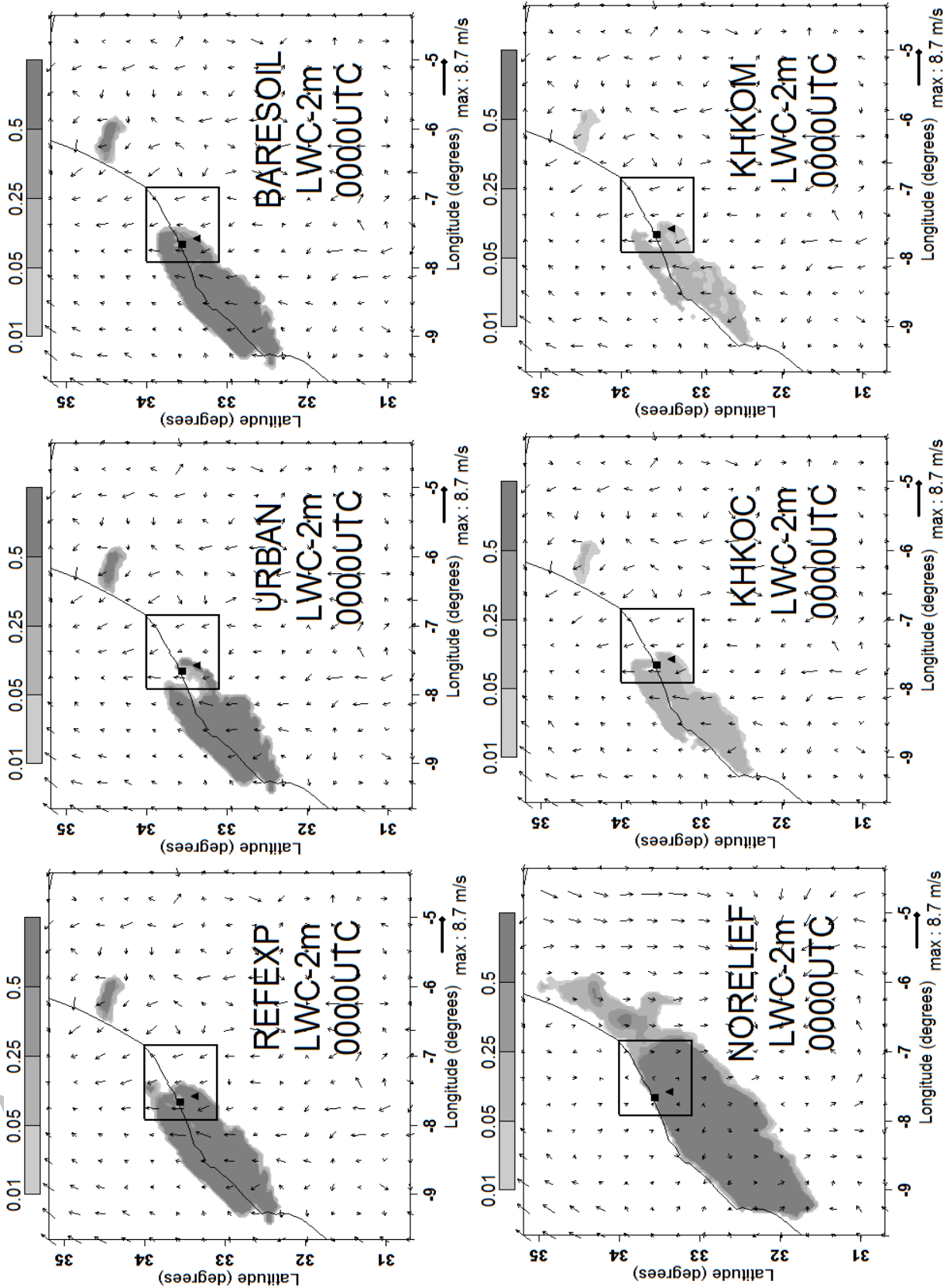


Fig. 11.

699

670