16.5 MESO- β AND γ SCALE ANALYSES, FORECASTS AND CLIMATOLOGIES OVER COMPLEX TERRAIN USING THE NCAR/ATEC REAL-TIME FDDA AND FORECAST (RTFDDA) SYSTEM

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1. INTRODUCTION

High-resolution weather analyses, forecasts and climatologies over complex terrain are very valuable and, sometimes, essential for many applications. However, analyzing and forecasting weather in complex terrain areas are very challenging, because 1) flows and environmental thermodynamic properties in these regions can be very complicated and contain rich detailed structures; 2) local circulations are controlled by interactions of multi-scale systems, and strong dynamic and thermodynamic forcing due to orography and/or heterogeneous underlying properties; and 3) observations are normally too sparse to properly describe either the macro- or micro- structures of local circulations.

In the last three years, NCAR, in collaboration with the Army Test and Evaluation Command (ATEC), has developed a multiscale weather analysis and forecast (RTFDDA) system. The system employs a Four-Dimensional Data Assimilation (FDDA) method, by which various observations are dynamically combined into a full-physicsmesoscale models, to generate real-time analyses and short-term forecasts on a set of multiscale domains. As of May 1, 2004, fourteen RTFDDA systems have been developed and operated within and outside of the United States. Among them, five have been operating at 5 Army test ranges, with fine-grids of 1.1 - 3.3 km, for operation periods varying from 2 to 3 years. The Army test ranges are located in very different geographic and climatological zones, e.g. from the White Sand Missile Range (WSMR) in New Mexico, to Aberdeen Test Center (ATC) in Maryland, to Cold Region Test Center (CRTC) in Alaska. Each of ranges possesses unique mountain range distributions and/or land use contrasts. In this paper, cases selected from the operational analyses and forecasts will be used to demonstrate the models capabilities of producing accurate real-time analysis and forecasts over complex terrain. A fine-scale climatological statistics are calculated using the archived hourly FDDA analyses at the test ranges.

2. MODEL AND DATA ASSIMILATION

The RTFDDA system is built around the Pennsylvania State University/National Center for Atmospheric Research (PSU/NCAR) mesoscale model (MM5V3). The first system started operation in October, 2000, at Dugway Proving Ground (DPG, Utah (Cram et al., 2001). Since then, many refinements and improvements have been carried out onto the data assimilation scheme and model physics (Liu et al. 2002, 2004). The model configuration used in the current RTFDDA systems can be summarized as following:

* Non-hydrostatic dynamics
* Two-way interactive nesting procedure
* Radiative upper boundary condition
* Time-dependent lateral boundary conditions relaxing toward large-scale models
* Grell cumulus parameterization on 10+ km grids.
* Reisner mixing-phase ice moisture scheme
* Modified MRF (or Hong-Pan) PBL scheme
* Cloud radiation schemes (Dudhia for shortwave and RRTM for long wave)
* Noah land-surface soil model

To simulate multi-scale weather interaction, a two-way nested-grid approach was employed. The grid increments of the model domains vary from a few hundred meters to tens of kilometers. As an example, Fig.1 show the domain configuration and the terrain and land-use on the finest mesh of the RTFDDA system running at the WSMR. By incorporating detailed terrain and land use information in the fine meshes, and using the synoptic-scale model output from national weather centers, the full physics high-resolution mesoscale model has proven itself capable of simulating various physical forcing factors and producing many realistic local circulations. To effectively combine these model advantages with all available observation, a Newtonian-relaxation-based continuous data assimilation technique, termed "observation-nudging", (Stauffer et al. 1994), is employed. With the "observation-nudging approach, an extra term is added to the model prediction equation(s) in order to keep the model solution close to the observations. Because of the complex forcing and evolution of local circulations over complex terrain, the spatial correlation can decrease very quickly with distance. Thus, the FDDA scheme is designed to allow the model to adjust toward observations at and near the observation time and location, and let the model to spread the observation information to other regions according to the model dynamics. When the system is set up for a specific region, it will start to run continuously to produce four-dimensional dynamically and physically consistent analyses, and in many cases, high-quality short-term forecasts are also produced at a

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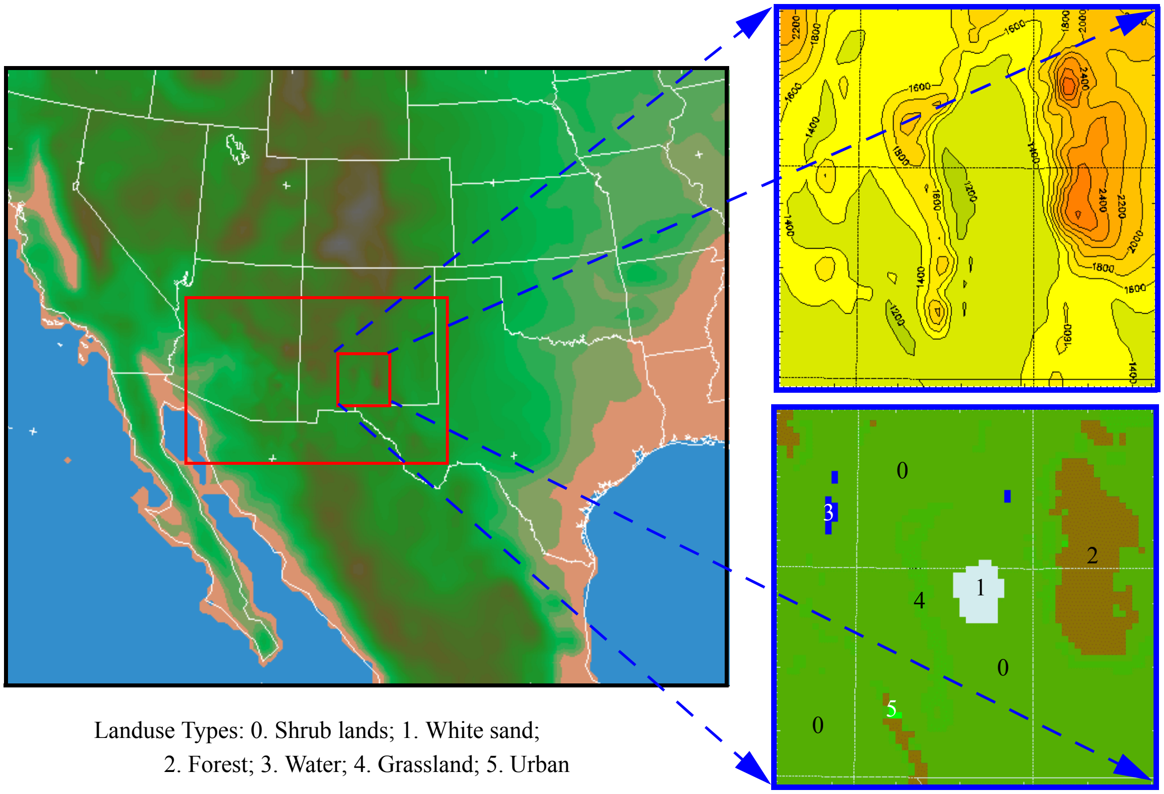

Fig.1 Domain Configuration, and the terrain and landuse distribution on the finest mesh of the WSMR RTFDDA system.

selected cycling interval of 1 - 12 hours based on application needs and availability of computer capacity.

The lack of sufficient observations on mesa-β and γ scales make it particularly important to incorporate both conventional and non-conventional observations, measured at both synoptic and asynoptic times. The data assimilation approach in the RTFDDA system has the ability to fully use these data. The data incorporated in the current system includes: the conventional twice-daily radiosondes; hourly surface, ship and buoy observations, and special observations from GTS/WMO; NOAA/NESDIS satellite winds derived from cloud, water vapor and IR imageries; NOAA/FSL aircraft reports of ACARS, AMDAR and others; NOAA/FSL NPN (NOAA Profiler Network) and CAP (Corporative Agencies Profilers) profilers; the 3-hourly cloud-drifting winds and water-vapor-derived winds from NOAA/NESDIS; and high-density, high-frequency observations from various mesonets, in particular, those from the Mesowest of the University of Utah.

3. ANALYSIS AND FORECAST EXAMPLES

Similar to large-scale weather models, mesoscale numerical weather prediction subjects to a problem of dynamic and diabatic "spin-ups" in the initial forecast stage. A model is normally started with initial conditions interpolated from larger-scale model outputs. Dynamically adjustments will take place in order to adapt the smooth model initial conditions to the steeper mesoscale terrain, sharper land-surface forcing contrasts, and other mesoscale dynamics. Furthermore, there is no proper cloud/precipitation observations to initialize the mesoscale models. With the FDDA approach, observations are dynamically incorporated into the model during the continuous model integration. Therefore, the RTFDDA system virtually remove the "spin-up" processes and is also capable of obtaining proper cloud and precipitation information indirectly through the model dynamic and physical processes during the observation assimilation. The model forecasts started from these dynamically consistent and diabatically initialized analyses present no artificial distortion. The shorter the forecasts, the more accurate the forecasts. Accordingly, in most application, frequent forecasting (cycling) are beneficial since by which more accurate forecasts with shorter forecast lengths are continuously updated in real-time.

To demonstrate this advantage of the RTFDDA system, two cases were selected, in which the RTFDDA forecasts are compared with "cold-started" forecasts: one is for March 9 and the other is for April 17, 2001, from the RTFDDA system running at DPG, Utah. The March 9 case was dominated by

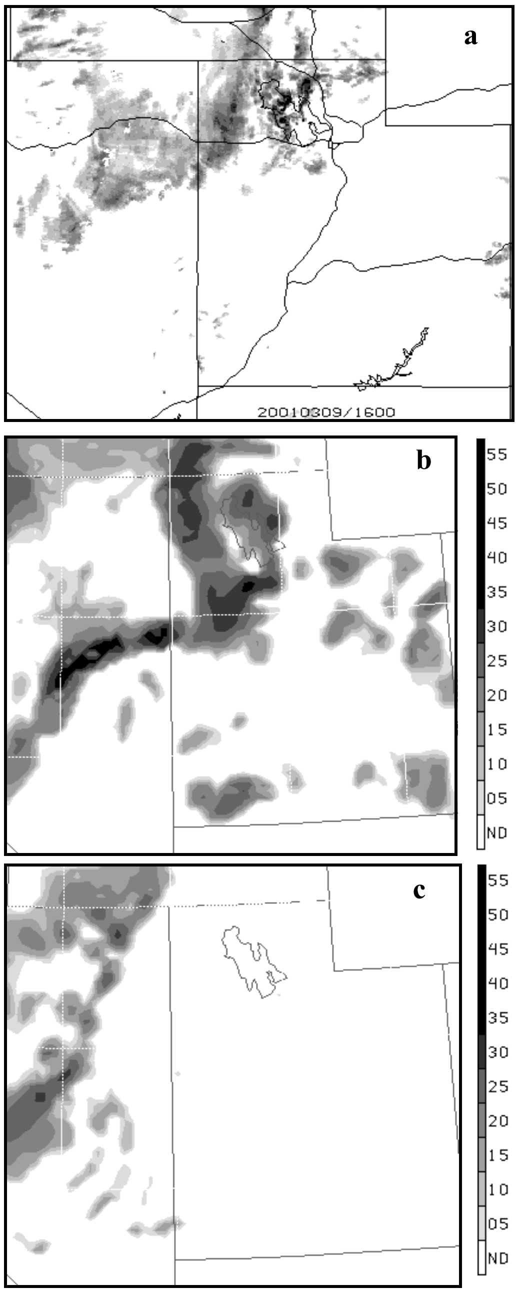

Fig.2 Comparison of radar reflectivity of observation (a), RTFDDA 0-h forecast (b) and "cold-start" 1-h forest (c) on domain 2 of the DPG RTFDDA system, valid at 16Z March 9, 2001.

snowfall from a slow-moving weak mesoscale frontal cycle over Utah area. In contrast, the April 17 case is chosen for its clear-sky situation controlled by a upper-air strong ridge and the lower level circulations in domain 2 and 3 were mainly forced by local terrain and land use contrasts.

On March 9, model verification against the surface observations (not shown) indicates that the "cold-started" forecasts present serious dryer bias and some warmer bias, over most area of Utah. However, the RTFDDA forecasts appears to significantly improve these errors. Analyzing various model fields found that the larger errors in the "cold-started" model forecasts are mainly caused by the phase errors of a frontal rain system. In this case, the cloud/rain "spin-up" process apparently leads to a slow development of the rainband. Fig. 2 compares snap-shots of the model reflectivities from the RTFDDA analysis (0h forecast) and the "cold-start" 1-h forecast, with the observation of the Utah NOWRAD, valid at 16Z, March 9. Obviously, the main frontal rainbands are much weaker in the "cold-start" forecasts and it is displaced to the west of the observed band. This displacement results in an overall warmer and dryer bias in the region. In contrast, the RTFDDA system produces a reasonably good precipitation intensity and location distribution, especially, in the Great Salt-Lake regions.

The clear-sky case of April 17 presents mainly locally-developed circulations forced by uneven underlying ground heating/cooling and terrain. In domains 2 and 3, various local circulation (with scales between 20 and 400 km) systems, including lake-breezes, mountain/valley breezes, salt-plate breezes, and others, can be clearly seen during the day. The surface verification indicates that the "cold-start" forecasts present a cold bias of -2.7 and -2.8 C on average for 0 - 12 hour forecasts. The FDDA analyses and short-term forecasts appear to dramatically correct the bias, with -0.3 C for the analyses, -0.8 C for 0 - 6 hour forecasts and -1.8 C for 7 - 12 h forecasts.

The surface temperature forecast in this case plays a significant role in determining the structure of the local circulations. Accordingly, the better initial surface temperature leads to better forecasts of the local circulations. Fig.3 compares the surface temperature and wind vectors on the Domain 3 (DX=3.3km) from the RTFDDA 4-h forecast and the "cold-start" 5-h forecasts, valid at 22Z (local afternoon), April 14, when the thermally driven circulations take maximum intensity. In both cases, upslope valley breezes can be found around mountain ridges. Although the overall resemblance, many discrepancies are evident. The most remarkable one can be found in the playa area located in the northwest quadrant of the domain. Playa possesses large heat capacity, high albedo, and high thermal conductivity, which results in much slower and less solar heating than the surrounding desert. Thus, salt breezes develop in the afternoon in clear-sky situations. The RTRFDDA forecasts (Fig.4a) shows a clearer salt-breeze structure than "cold-start" forecasts (Fig.4b). Fig.4c indicates that the RTFDDA cycle predicts much warmer and better temperature in the desert area to the east and south of the playa, enhancing the flow from playa to the desert. The warmer desert also strengthens the lake breeze from the Salt Lake (northeast corner of the

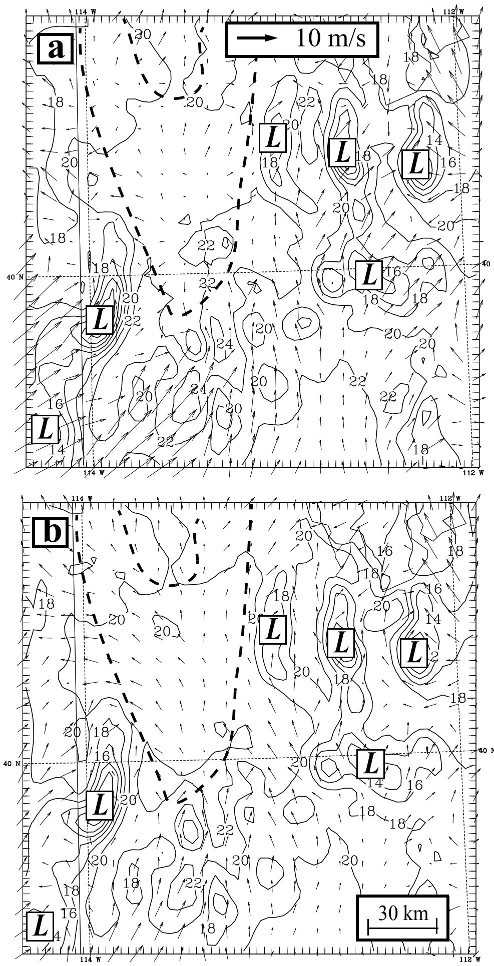

Fig.3 Surface wind vectors and temperature of the RTFDDA 4-h forecast (a), "cold-start" 5-h forecast (b) on domain 3 of the DPG RTFDDA system, valid at 23Z Apr. 17, 2001. Low temperature center corresponding to major ridges are labelled with "L". The thick dashed line marks roughly the playa-desert boundary.

domain) and modifies locally the large scale upslope breeze driven by large ranges in Nevada to the west and valley flow to the southwest of the domain.

4. REGIONAL CLIMATE STATISTICS

Mesoscale circulations are controlled by two major forcing factors: 1). synoptic control flows and their interactions with local mesoscale terrain, and 2). development of local circulations driven by uneven surface heating/cooling processes due to the heterogeneous land surface properties and land-water contrasts. Mesoscale weather on a particular day and time is determined by the relative forcing strength and dominance of these two factors, which can lead to dramatic weather changes. Historically, to study the effect of local forcings, either idealized modeling or weather cases dominated by one forcing factor, such as flows over and/or surrounding mountains, mountain-valley breezes, sea breazes and others were selected for detailed analyses. On the other hand, regional climate models and simulations were also carried out by modelers to study the local climate by nesting a mesoscale model in a GCM. The daily weather and circulation details from these models may not be accurate, but some climate features can be inferred.

The real-time (and/or retrospective) accurate high-resolution continuous 4-D analyses from the RTFDDA systems provided a unique dataset for studying the roles of the local forcings in terms of both daily local weather and regional climate. Since the RTFDDA systems have just been running for 2 - 3 years, which have not produced sufficient output for computing multi-year climates, hereby we study the regional "climate" by computing monthly average of the RTFDDA analyses. Regional climates may vary with seasons and time of day. However, it is not the intension of this paper to describe a complete local climate of selected regions. Instead, here we are focusing on a few controlling factors responsible for the local climate formation. Two examples with different weather and climate regimes are shown here.

4.1 Mountainous WSMR (NM) regions

The WMSR region (Domain 3 of the WSMR RTFDDA system; cf. Fig.1 and Fig.4a) features two mountain ranges: the Sacramentos Mountains to the east and San Adres Mountains to the west. Between the two ranges is the big and flat valley of Tularosa Basins. The land use in the region are dominated by shrub lands, with patches of forest spreading over mountains. The White Sand monument, located in the middle of the valley, presents a unique land-surface property contrasting to the surrounding shrub lands.

Monthly average of the RTFDDA analyses in the early spring displays clear dominance of the local thermal-driven mountain-valley circulations in the region. Valley breezes converge toward the mountain ridges in the day time and mountain breezes drain downslope to the lower valleys. However, analyses of the detailed the circulation structures indicated that the mountain-valley circulations are significantly distorted by the large scale prevailing westerlies in the high mountains. The dynamic interactions between the local terrain, the incoming large scale flow and the locally developed small scale flows are prominent.

Fig. 4 shows the monthly mean surface winds at 12:00 UTC (local time of early morning), for the March of 2004. A few interesting features can be observed. Firstly, evident downslope mountain breezes can be observed along both sides of the San Adres Mountains with stronger flows developed over the steep and higher ridges. Secondly, downslope flows over the two sides of the mountain ranges display very asymmetric structures, with much stronger winds on the east slope (the wind zone in center region of Fig 4b).

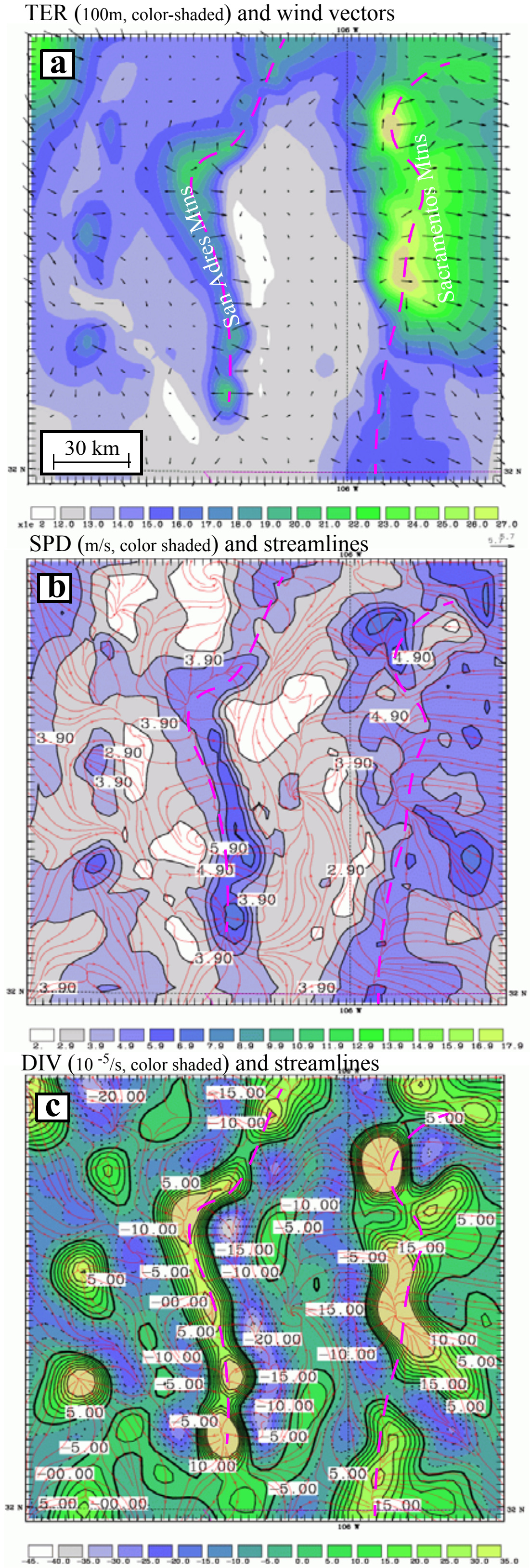

Fig.4 Terrain height, monthly averaged surface wind speed and divergence on the domain 3 of the WSMR RTFDDA system for the March of 2004 , valid at 1200 UTC. The averaged wind vectors and stream lines are superposed. The ridges of the two major mountain ranges are marked by dashed magenta lines..

The winds on the east slope are generally 2-4 m/s stronger than those on the west slope. The downslope winds on the east slope generate a strong convergence zone along the foothills in the Tularosa Basin. Thirdly, the mountain winds over the Sacramentos Mountains display similar asymmetric but more complicated structures. Superposed on the mountain breeze are flow components circulated around the two high peaks of the mountains. A broad area of strong downslope flows can be seen over the east slope of the mountain, which has high elevation and less steepness. Fourthly, the White Sand area is characterized by a local convergence center. The asymmetric distribution of the mountain breezes indicates a large modulation of the thermal-driven circulations by extra forces. In fact, vertical cross-sections normal to the mountains (not shown) expose clearly a direct interaction between the mountain breezes and the prevailing synoptic-scale westerlies. The westerlies, which increases with heights, counteract against the downslope breezes over the west slope, but intensify the ones on the east. The broad strong wind zone over the east slope of the Sacramentos Mountains are associated with the strong west winds due to its high elevated terrain. It can been seen in Fig. 4c that complex local divergence structures are generated by the interactions between the local circulations and the large-scale prevailing winds. In the night and early morning, the divergence centers of the mountain breezes appears to be preferably located to the west of the ridges.

The asymmetric structures and flow interactions change diurnally in response to the surface heating/cooling evolution and PBL development. Nevertheless, the superposition of the local and the prevailing winds appears to take a control role on the formation of pthe basic local circulation patterns. For example, in the early afternoon (not shown), upslope valley breezes develop. The westerlies tend to speed up the valley winds on the west slopes of the mountain ridges, but counterflowl those on the east. In this case, convergence zones are preferably developed right to the east of the ridge-lines.

4.2 Chesapeake Bay ATC (MD) regions

Unlike the mountainous feature over the WSMR region, the fine mesh of the ATC RTFDDA system is dominated by relatively flat terrain with strong land-water contrasts (Fig. 6a). The northwest half of the domain features with small hills of a few hundred meters height, while in the southeast half, two bays, the Chesapeake Bay and the Delaware Bay, protrude toward the northwest into the flat lower land.

Two local forcing regimes affect the formation of the mesoscale circulations in the region. One is the thermal forcing of the hilly terrain and the other is the land water contrasts. Unlike the dominant effect of locally thermal-forces in the WSMR spring case, statistical average of RTFDDA analyses in this region, for the April of 2004, exhibits a more important role of the prevailing large-scale flows in the development of the local circulations. The local forcing is secondary, which mainly modulates the impinging large scale flows.

The monthly average surface winds at 12Z (early morning of local time) in the region (Fig.5) display a rather uniform large-scale flow pattern, with wind speeds of 3 - 5 m/s over land and up to 7 - 9 m/s over the water bodies. The prevailing wind blows mostly from the west, with slightly northern components in the up hilly regions and southern components in the down flat region between the two bays. The northern components in the hilly regions are mostly

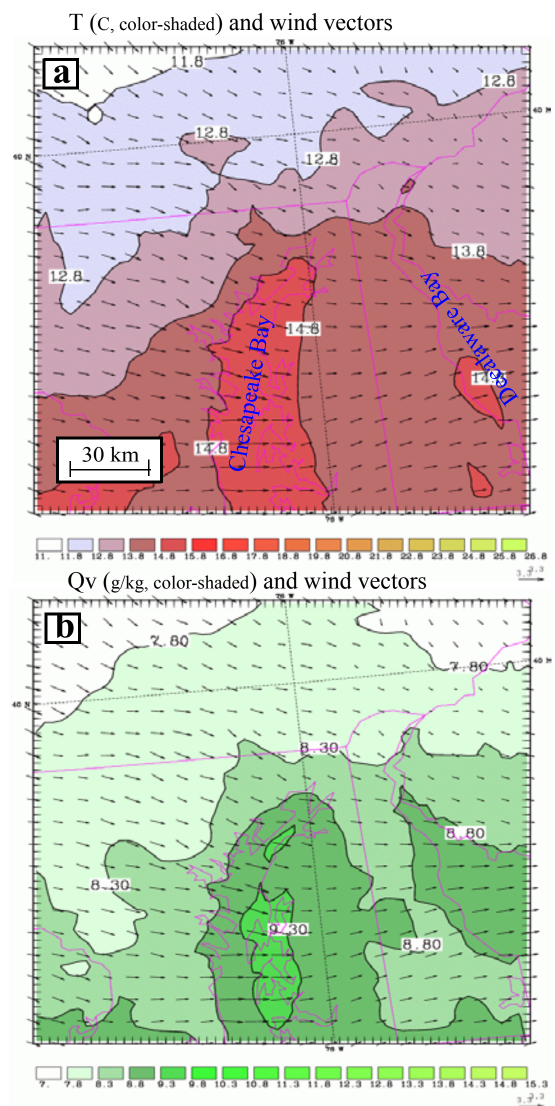

Fig.5 Terrain height, monthly averaged surface temperature and moisture mixing ratio on the domain 3 of the ATC RTFDDA system for the April of 2004, valid at 1200 UTC. The averaged wind vectors are superposed.

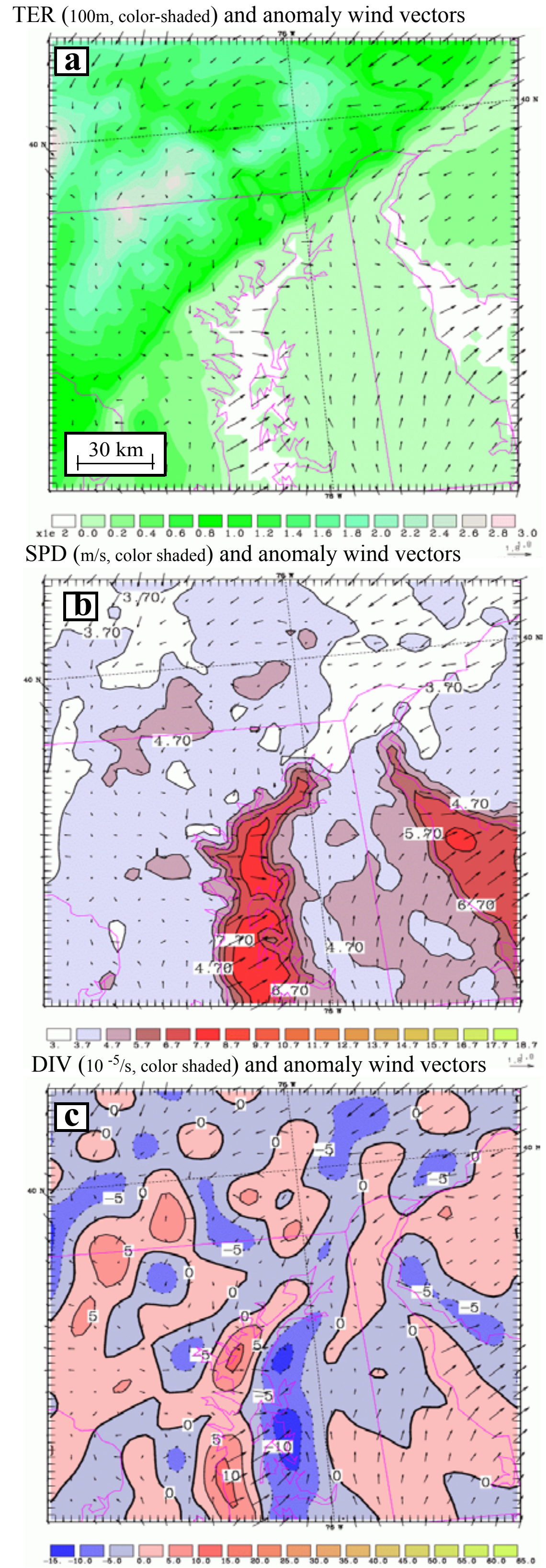

Fig.6 Same as Fig.5, but for terrain height, monthly averaged surface wind speed and divergence fields. Note that superposed are anomaly wind vectors.

associated with drainage downslope flows (Fig.6a) at the time. The variation of winds in the bay areas worthies more discussions. Essentially, the interaction between the prevailing flows and the warm bay water bodies are mostly responsible for the local wind variations. First, the prevailing winds tend to shift the warm and moist air above the bays downwindward. Fig, 5a and b show evident warm and moist bay air cores located close to the east shore of the Chesapeake Bay. Second, due to much smaller friction over water surface, the incoming large-scale winds start rapidly speeding-up as they enters the water regions and decelerate sharply while exiting the bays. These processes result in a formation of the strong winds over the bays and in the downwind shore regions (Fig. 6b). The sharp changes of winds across the bay lead to a development of strong divergence and convergence zones along the upwind shores and downwind shores respectively (Fig.6c). To further study the forcing mechanisms of the local forcing, anomaly wind vectors -- the total wind vectors (at each grid point) minus the domain-average of surface wind vector -- are calculated and plotted in Fig.6. Obviously, the acceleration of the prevailing winds over the bays produce significant extra momentum residues. The anomaly wind vectors surrounding the Chesapeake Bay shows a trend of the flows converging toward the warm moist bay air bubbles. More interestingly and importantly, an evident broad southernly stream appears to flow into the domain from the south boundary of the domain, extending to the whole bay and surrounding regions. This wind component is forced by a large-scale circulation in association with the large semi-permanent high pressure system centered over the Atlantic Ocean near 30 degrees north latitude in the vicinity of Bermuda. The smooth and broad bay surface opens a channel for this wind to travel deeply in-land along the bays. It is this wind component that, in combination with the "sped-up" residue of the prevailing west wind, produces the southwest winds over the bay waters.

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