ENVIRONMENTAL FLUID MOTIONS

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ABSTRACT

The Ecosphere, which sustains life on Earth, encompasses two major fluid masses -- the atmosphere and oceans. Both of these fluid bodies are in turbulent motion, driven by thermal forcing (e.g. temperature gradients) induced by solar radiation and to a lesser extent by gravitational forcing exerted by celestial objects (e.g. tidal forcing). External forcing occurs over a myriad of well-defined space-time scales, but instabilities and strong non-linearities of resulting fluid motions lead to an almost continuous spectrum of mutually interacting flow phenomena. The scales of external forcing and those imposed by the density stratification (buoyancy effects) and Earth's rotation (Coriolis forces), however, leave imprints in the spectrum signifying distinct flow regimes with intrinsic dynamical balances. Large-scale motions affected by Earth's rotation tend to be strongly anisotropic, the study of which falls in the realm of Geophysical Fluid Dynamics. The "urban" and "man" scale motions, on the other hand, are dominated by the turbulence phenomenon and are dealt in Environmental Fluid Dynamics. Collectively, all scales of motions and their complex interactions with physical, chemical and biological processes help to maintain the properties of the Ecosphere within narrow windows conducive for the existence of life, yet such motions exhibit profound variability and incredible diversity that defy predictability. Some dominant flow phenomena occurring in the atmosphere and oceans, dynamical processes leading to such motions, and issues related to their prediction (forecasting) are briefly discussed in this paper.

1. INTRODUCTION

Earth scientists classify the outer layers of the Earth into four main realms, the lithosphere (outer layer of the solid earth), the atmosphere (gaseous layer to a height of ~100km), the hydrosphere (layer of water covering the planet, that includes oceans, lakes and rivers) and the biosphere (layer of organic matter covering the land surface, with a thickness of several meters). Human beings and other 1.4 million formally classified species of animals and plants are a part of the biosphere (Wilson 1989), which dynamically, chemically and biologically interacts with the other three spheres to form the complex environment of the Ecosphere. Properties such as the temperature and constituents of the Ecosphere are maintained within narrow windows by a host of mutually interacting processes, for which ecospheric fluid (air, water and tectonic) motions contribute greatly. In particular, atmospheric and oceanic motions play a major role in determining the property distributions in the Ecosphere, wherein such motions are responsible for the transport and mixing of properties over different space and time scales. Solar radiation acts as the prime mover for environmental fluid motions, providing necessary temperature gradients (baroclinicity) to initiate and maintain large-scale motion fields. For example, differential solar insolation between equatorial and polar atmospheres, over scales on the order of 10^4 km, is the major thermal anomaly that drives global atmospheric circulation. Warm air rising from the tropics and cold air sinking at high latitudes (i.e. thermal convective flows) lead to the meridional (or Hadley) circulation in the atmosphere. Earth's Coriolis forces deflect such flows in east-west directions, generating major airflow patterns, such as the jet stream, that transport airborne particulate matter and liquid droplets (aerosols) over long distances. The Coriolis force is also a necessary ingredient for the baroclinic instability, which is responsible for the breakdown of baroclinically driven flows to form eddies (e.g. high and low-pressure regions in the atmosphere). A similar situation arises in oceans, wherein warm waters in tropics are transported along the surface layer toward polar seas where they cool, sink and spread back toward low latitudes. A combination of high-latitude convection, low latitude upwelling and mixing between pole-ward and equator-ward flows in upper and lower layers of major oceans determine the major pathways and thermal and salinity structure of oceanic flows. Large-scale motions so generated are degenerated into smaller scales *via* instabilities and turbulence, thus generating a continuum of scales from Hadley cells to Kolmogorov (turbulent-energy) dissipating scales. Different scales of motions interact, cascading energy and other properties between different scales, toward larger or smaller scales, depending on dynamical processes at work. For example, megameter-scale thermal anomalies in the atmosphere and oceans are dissipated at millimeter-scale turbulent eddies whereas chlorofluorocarbons added to the atmosphere as a consequence of "man-scale" releases of refrigerants and aerosol propellants are transported and dispersed over thousands of kilometers to produce the "ozone hole" over Antarctica.

Prediction of how fluid masses in the Ecosphere forced at distinct space-time scales lead to an almost continuous spectrum of mutually-interacting fluid motions is at the heart of environmental forecasting. The field of *Geophysical Fluid Dynamics* (GFD) traditionally deals with large-scale ecospheric motions, strongly dominated by Earth's Coriolis and buoyancy forces (climatology, meteorology and large-scale physical oceanography are components of this subject). Large-scale motions feed into smaller (1m-10km) scales that directly affect the biosphere -- the immediate environment of human beings and other life forms. The study of such motion scales is in the domain of *Environmental Fluid Dynamics* (EFD). Investigations of urban and suburban (man)-scale (or micro-meteorological) motion fields, their role in the dispersion of chemical compounds in the biosphere and risks posed thereof are some salient topics of EFD. Small-scale ocean mixing and limnology are also considered as components of EFD. *Ecological Fluid Mechanics* integrates environmental fluid mechanics with biological (mainly plant and animal species) activities and habitat dynamics. The study of lithospheric (tectonics, flow through rock fabrics etc.) motions is in the realm of *Geological Fluid Dynamics*. Demarcations between these different "cousins" of fluid mechanics are not sharp, but the existence of such a variety of focus areas to study ecospheric motions indeed points to the complexity, utility and preponderance of such fluid motions.

2. SCALES OF MOTION

Environmental fluid motions are described by usual conservation laws for mass, momentum and energy. In the usual notation, the non-dimensional form of mass conservation equation becomes

$$\frac{L_v}{T_\rho w_o}\frac{\partial \rho}{\partial t}+\left(\frac{u_o}{L_H}\frac{L_v}{w_o}\right)\frac{\partial \rho u_\alpha}{\partial x_\alpha}+\frac{\partial \rho w}{\partial z}=0, \qquad \alpha = 1, 2\,, \qquad (2.1)$$

where L_v and L_H are the characteristic vertical and horizontal length scales, z is the vertical coordinate, T_ρ is the time scale of density variations and w_o and u_o are the characteristic vertical and horizontal velocity scales. When $L_v / T_\rho w_o \ll 1$, acoustic waves are filtered out, thus yielding the balance u_o/L_H ~ w_o/L_v and $\partial \rho u_i / \partial x_i = 0$ (anelastic approximation). The horizontal and vertical momentum equations, thence, can be written as

$$\left(\frac{L_H}{u_o T_o}\right)\frac{\partial u_\alpha}{\partial t}+u_\alpha\frac{\partial u_\alpha}{\partial x_\alpha}+w\frac{\partial u_\alpha}{\partial z}+\left(\frac{f_v L_H}{u_o}\right)\varepsilon_{\alpha ij} l_i u_j =$$

$$-\frac{p_o}{\rho u_o^2}\frac{\partial p}{\partial x_\alpha}+\frac{F_\alpha L_H}{u_o^2}+\left(\frac{\nu}{u_o L_H}\right)\left[\frac{\partial^2 u_\alpha}{\partial x_\alpha^2}+\left(\frac{L_H}{L_v}\right)^2\frac{\partial^2 u_\alpha}{\partial z^2}\right]$$

$$\alpha = 1, 2 \qquad (2.2),$$

and

$$\left(\frac{L_v}{L_H}\right)^2\left[\left(\frac{L_H}{u_o T_o}\right)\frac{\partial w}{\partial t}+u_\alpha\frac{\partial w}{\partial x_\alpha}+w\frac{\partial w}{\partial z}\right]+\left(\frac{f_H L_H}{u_o}\right)\left(\frac{L_v}{L_H}\right)\varepsilon_{3ij} l_i u_j$$

$$=-\frac{p_o}{\rho u_o^2}\frac{\partial p}{\partial z}-g\frac{L_v}{u_o^2}+\frac{\nu}{u_o L_H}\left[\left(\frac{L_v}{L_H}\right)^2\frac{\partial^2 w}{\partial x_\alpha^2}+\frac{\partial^2 w}{\partial z^2}\right], \qquad (2.3)$$

where p_o and T_o are the characteristic pressure and time scale of motion, f_v and f_H are the scales of vertical and horizontal components of Coriolis parameter and $\tilde{l}$ is the unit vector in the direction of Coriolis parameter. For temperate (30-60^0) and high latitudes, $f_H \approx 0.$ Ecospheric motions are usually classified according to the order of magnitudes of L_o and T_o. When T_o is on the order of a few days to months, the motion field belongs to the category of *synoptic flows*, with typical length-scales of the order $L_H \sim 10^3 - 10^4$ km (regional to intercontinental scales) for the atmosphere and $10^2 - 10^3$ km for oceans. Scales of T_o ~ 1 hr to 1 day represent typical atmospheric scales of $L_H \sim 10^2 - 10^3$ km and oceanic scales of 10 km, whence motions belong to *meso-scale* category. Much of the forcing of ecospheric motions occurs at synoptic and meso scales, and hence they play a major role in the generation and maintenance of small-scale motions (T_o ~ fraction of a second to tens of minutes). Since the thicknesses of oceans (~ 5 km) and the atmosphere (~ 30 km; 95% of the air mass resides below this level) enveloping the Earth are much smaller than the horizontal scales of synoptic motions, the vertical momentum equation (2.3) for such motions at high Reynolds numbers ($\mathrm{Re} = {}_H L_H / \nu \gg 1$) can be treated as hydrostatic. Similarly, the vertical accelerations or the non-hydrostatic nature become significant in meso-scale flows. Equations (2.2) and (2.3) subject to the condition $L_v / L_H \ll 1$ are the starting points of the well-known shallow water theory in GFD that underpins analyses of large-scale flows (Pedlosky 1982).

In numerical models dealing with oceanic and atmospheric general circulation, synoptic-scale motions are resolved. Meso-scale motions are also captured in some high-resolution regional models. Small-scale motions, mainly consisting of turbulence, are not resolved in environmental forecasting models, wherein the effects of small scales need to be parameterized. The development of sound closure schemes, therefore, is one of the major challenges in environmental fluid mechanics.

3. DYNAMICAL BALANCES

The force balances that exist in distinct scales of environmental motions are different and are determined by the dominant terms of (2.2) and (2.3). These motion fields are in a continuous state of evolution and their average properties are sensitively determined by the averaging period as well as the locality and time information. By selecting suitable averaging periods, however, it is possible to educe some intriguing flow states having special properties that are representative of the space-time scales of interest (Nastrom et al. 1984). For example, when $f_H \sim 0$, Re >> 1, $L_H / u_0 \tau_0$ <<1, $F_\alpha L_H / u_0^2$<<1 and at small Rossby numbers $Ro = u_o / f_v L_H$<<1, (2.2) assumes the state of *Geostrophy*, satisfying the relation $\tilde{f} \times \tilde{u} = -\rho^{-1} \nabla p$. Geostophically balanced flows abound in nature, some example being high and low pressure regions in the atmosphere, oceanic eddies (e.g. Gulf-stream rings) and large-scale ocean currents. The geostrophic balance is responsible for the maintenance of the jet stream. This majestic upper-level air stream of the Northern Hemisphere is often utilized by aviators as a beneficial tailwind and the aerosols suspended in it are capable of circumnavigating the Earth in four to five days. At heights of 10km or so, the pressure in warmer low latitudes is less than that of colder high latitudes, and the resulting equator-ward pressure gradient forces (~ 10^{-2} m^2/s) in conjunction with Coriolis forces (f ~ 10^{-4} s^{-1}) develop (westerly) jet-stream having speeds on the order of 200 miles/hr.

It is clear that the geostrophic balance can only be realized at some distances away from the Earth's surface, because the frictional resistance is an important factor near the surface; the flow near the boundaries, therefore, is analyzed as consisting of geostrophic and ageostrophic components. From the dynamical balances of (2.2), it is clear that the frictional forces preclude the achievement of geostrophy in a layer of vertical thickness $(\nu / f)^{1/2}$, which is the scale of the Ekman layer. In environmental flows, the frictional resistance is dominated by turbulent stresses represented by an eddy viscosity κ, and hence the Ekman layer thickness in the atmosphere can be estimated as $(\kappa / f)^{1/2}$. For typical values of κ = 5m^2/s and f = 1x10^{-4} s^{-1}, it is possible to obtain $(\kappa / f)^{1/2}$~200 m. Below this height, the effects of Earth's rotation on the flow is negligible and far above it the geostrophic balance is achieved.

4. SMALL-SCALE MOTIONS

Small-scale turbulent motions in the atmosphere and in oceans control the meter-scale flows that directly affect human activity. These motions often represent the degeneration of large-scale motions, for example, breakup of mesoscale eddies in the atmosphere or turbulence production in equatorial undercurrent system over vertical scales of tens of meters. Small-scale motions can also be produced locally, in the absence of large-scale motions, for example, by the thermal convection occurring during the daytime solar heating or by flows driven by local temperature inhomogeneities. Flows in complex topographies, such as those found in areas replete with mountains, escarpments and significant roughness, fall into this latter category. In the absence of synoptic flows, the air circulation in complex terrain is completely determined by local thermal inhomogeneities.

As stated before, the small-scale motions are not resolved in predictive models and increasing attention is being given to understand the physics of small-scale motions and to parameterize them using physically sound formulations. The need for better parameterizations is clearly demonstrated by the fact that predictions of most of the available models are sensitive to the type of parameterizations used (Fernando & Hunt 1996). The following discussion illustrates the importance of small-scale processes in determining the states of oceanic and atmospheric motions as well as their predictability.

The first few hundred meters of the atmosphere are profoundly influenced by diurnal radiative heating and cooling and by the land surface. The region in which the ground influence is dominant is defined as the Atmospheric Boundary Layer (ABL), and it encompasses a major part of the biosphere. Figure 1 shows a schematic of processes occurring during the diurnal cycle of ABL over a flat terrain. After the sunset, cooling of the ground causes the generation of a stable layer near the ground, which grows into the night and achieves its maximum thickness in the early morning. Influence of synoptic and meso scale pressure gradients lead to a mean airflow in the stable boundary layer (SBL); cooler air layers near the ground move slower than the overlying air, leading to a stratified shear flow in the form of a low-level jet. The upper layers of this nocturnal (stable) boundary layer (SBL) is de-coupled from the lower layers, and strong shear leads to the generation of shear instabilities such as Kelvin-Helmholtz (K-H) billows. Mixing associated with K-H billowing causes aerosols to mix downward, thereby transporting contaminants suspended in upper-level flow to the ground (Nappo 1991).

It is common to classify a SBL based on the degree of "stability," quantified by a suitably defined gradient Richardson number $Ri_g = N^2 / (\partial \overline{U} / \partial z)^2$, where $\partial \overline{U} / \partial z$ is the mean velocity shear and N is the buoyancy frequency. The case of $Ri_g > 1$ is called the very stable boundary layer, characterized by light winds, layered structure and intermittent turbulence wherein Monin-Obukhov (M-O) theory is invalid (Mahrt 1998). In the weakly stable case (0.25< Ri_g <1), on the other hand, significant winds maintain more or less continuous turbulence, describable by the M-O theory. Lacking a mechanism to induce significant <u>mean</u> vertical motions, the vertical transport in flat-terrain SBLs is mainly realized by turbulence (Hunt 1985; Weber & Kurzeja 1991; Fernando & Hunt 1996). Since vertical displacements of fluid parcels in stratified turbulence are constrained by the buoyancy length scale σ_w / N, where σ_w is a characteristic (r.m.s.) vertical velocity (Hunt 1985), the vertical transport and mixing in the SBL are meager.

In the morning, after the sunrise, the buoyant production of turbulence causes the development of a convective boundary layer (CBL), which grows against the stable stratification. The CBL is separated from the stratified layer aloft by a density interface (capping inversion). During the CBL growth, the pollutants trapped in the stable layer are mixed upward and diluted, thus reducing the concentration of pollutants near the ground. Figure 2 shows the measurements of small particulate matter, both fine and coarse particles, during the diurnal ABL cycle of the Phoenix metropolitan area. Note the reduction of pollutant concentrations with the growth of the CBL. The nature of turbulence in and associated scaling for the CBL have been well studied and established, but the dynamics of turbulence in the SBL and during the transition between stable and unstable periods and *vice versa* have not been studied in detail. Much work is required to develop parameterizations for stable and transition periods. Since the air pollution in populated cities is exacerbated during morning and evening transition periods due to rush-hour traffic, there is an acute need to incorporate sound turbulence parameterizations for the prediction of flow in transition periods. These aspects will be addressed in a multi-agency field project entitled "Cooperative Atmospheric Surface Exchange Study" (CASES-99) to be carried out in the Fall of 1999.

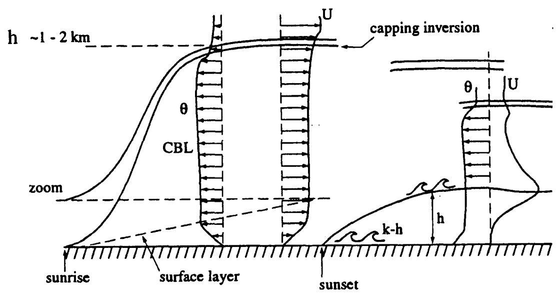

Figure 1 Diurnal cycle of the atmospheric boundary layer over flat terrain. θ is the potential temperature, U is the velocity and h is the ABL height.

In cities located in complex topographies (complex-terrain airsheds), such as many cities in the desert southwest of U.S., the ABL is complicated by the presence of side boundaries in the form of surrounding mountains; see Figure 3 that shows the undulating topography of the Phoenix metropolitan area. Also shown in the figure are the locations of forty four routine monitoring stations of ground-level meteorological variables (Phoenix Meteorological Network) operated by various agencies. Simple scenarios presented in Figure 1 are inapplicable to areas such as Phoenix, where local wind patterns are dominated by thermally induced flows generated on surrounding slopes. The data taken by the Phoenix meteorological network clearly indicate that the cooling at night generates down-slope (katabatic) flows along the mountain slopes, which drains into the semi-open basin of Phoenix. Flows originating at nearby slopes (10 km scale) arrive at the city center first, followed by those originating at mountain ranges as far as 100 km away. The nocturnal flows in the basin, therefore, tend to be a complex and take the form of a skewed stratified shear flow. The SBL in complex-terrain basins typically satisfy $Ri_g \sim 1$, and hence tends to be weakly turbulent. Most of the work so far reported on complex-terrain airsheds has been focused on bulk features of the flow, and future work should deal with the details of turbulence and transport processes.

A situation analogous to ABL arises in the upper ocean in response to the diurnal heating and cooling of the surface layer. Stable stratification develops during the daytime warming of the surface layer, the thickness of which is determined by a balance between wind stirring and development of stable stratification. As a result, the turbulent layer assumes a depth proportional to the M-O length-scale (Brainerd & Gregg 1993). Unstable stratification forms at night, developing a CBL. Typically, such CBL's coexist with velocity shear, causing the amplification of turbulence (Moum et al. 1986).

Wind stirring in the upper layers accounts for only 60% of oceanic small-scale mixing, and other major mechanisms of ocean mixing have eluded detection by conventional oceanic microstructure measurement techniques. Recently, Munk & Wunsch (1998) have argued that the remaining 40% of the energy required for oceanic mixing is provided by oceanic internal tides, generated by the interaction of barotropic tides with long topographic features. Convincing evidence for this conjecture is yet to be provided by field measurements.

5. ENVIRONMENTAL PREDICTIONS

A host of numerical models is currently available for the prediction of atmospheric flows, each offering specific advantages and drawbacks with respect to implementation, scale of prediction and performance. Most of the available models solve primitive equations, employing closure assumptions to account for unresolved scales. General circulation models are designed to predict synoptic flows, and at present their horizontal and vertical resolutions are on the order of 100km and tens of meters, respectively. Higher resolutions (e.g. meso and urban scales) can be obtained by restricting the domain (regional models) or by grid nesting (i.e., successive refinement of calculations in selected areas by employing the output based on one grid size as the input condition for calculations with another grid size). Commonly used meso-scale models for urban forecasting include RAMS (Pielke, 1984), HOTMAC (Yamada & Bunker 1988) and MM5. With nested grids and meso-scale models, resolutions as high as 40 m have been obtained in urban micrometeorological predictions (Cionco & Ellefsen 1998). The outputs of the meteorological models can also be interfaced with special purpose modules such as urban-street-canyon and traffic-induced pollution models to achieve resolution on the order of a few meters (Berkowicz et al. 1997).

Figure 4 illustrates the performance of the HOTMAC meso-scale model developed at the Los Alamos National Laboratory, as applied to the Phoenix area. The predictions were made for January 30, 1998 -- a typical day during the winter field experiment known as the Phoenix AirFlow Experiment (PAFEX-1), carried out at the Grand Canyon University premises (Figure 3). This field program was designed to investigate the thermally driven flow in the Phoenix area in the winter and to relate meteorological fields to the distribution of particulate matter and CO. For initialization, HOTMAC requires the vertical profiles of potential temperature and relative humidity, and the solutions are "nudged" at specific times by using upper-level wind, potential-temperature and humidity profiles. For initialization and nudging of the simulations shown, radiosonde launches by the National Weather Service Offices in Tucson or Flagstaff have been used. The calculations were performed with 16km coarse grid, nested down to 1km, with 21 vertical layers having 5m resolution in the first 25m and exponentially increasing grid size thereafter up to 6km. The velocity measured in the first few tens of meters during PAFEX-1 is reasonably well predicted by the model calculations performed with 1km grid and Flagstaff radiosonde data. Marked disagreements between the data and predictions could be seen, however, for coarser grids and when using Tucson radiosonde data; this may be due to the highly variable weather patterns that existed in Tucson during that day. Comparative studies made using different sub-grid parameterizations indicate that the predictions are indeed sensitive to the type of parameterizations employed in the model (Berestov & Brown 1997). The overall PAFEX measurement and associated numerical modeling program, in general, clearly pointed out the importance of developing refined parameterizations for environmental forecasting models.

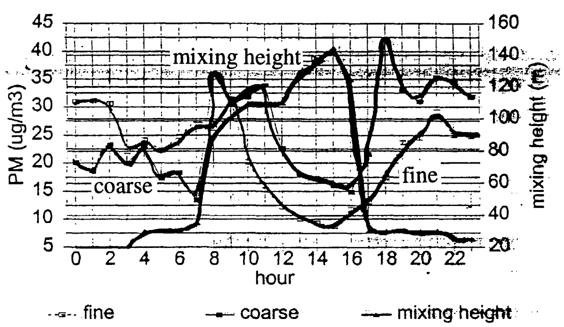

Figure 2 The variation of the mixing height and fine and coarse particles in the Phoenix area during the diurnal cycle (courtesy: Peter Hyde, Arizona Department of Environmental Quality)

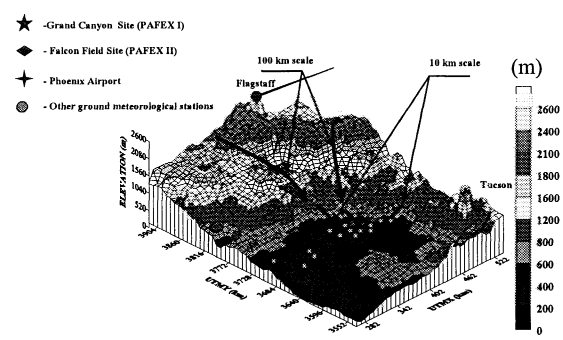

Figure 3. The complex-terrain airshed of Phoenix. The sites of routine meteorological measurements (stipples) and the location of Grand Canyon University (GCU) where the PAFEX-1 experiment was carried out are shown. The Falcon field airport, where the summer experiments (PAFEX-II) were performed, is also indicated.

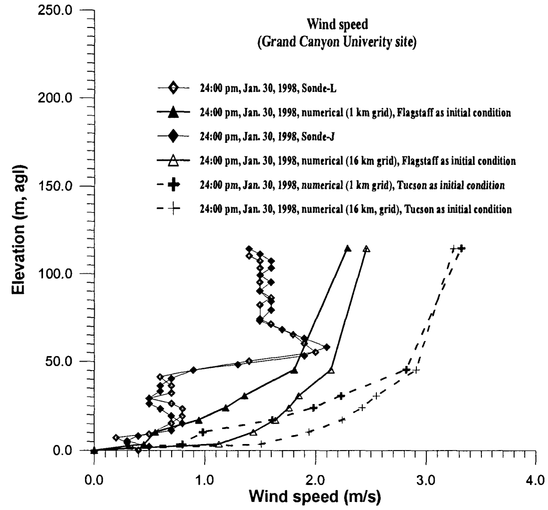

Figure 4. A comparison between measured wind speeds using two sondes (J and L) at midnight on Jan. 30, 1998 (during PAFEX-I) and HOTMAC predictions. The sondes were attached to a vertically traversing tethered balloon. The calculations were performed using 16-4-1 km grid nesting. Calculations for different initial conditions (based on Tucson and Phoenix radiosonde launches) are shown.

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