Is MM5 good enough for air-quality models?

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Abstract:

The MM5 mesoscale meteorological model at the University of Washington does very well [$\boldsymbol{R}^2$ up to +0.91] with 12-hr forecasts of wind speeds and directions at four RAWIN sites in the Pacific Northwest, when the observed wind speeds exceed 5 m/s. With wind speeds less than 5 m/s, however, this model does worse than climatology [$\boldsymbol{R}^2 < 0$] at all sites and elevations. As air pollution thrives near the surface in light winds, prudent caution should be exercised by users of MM5 winds with air-quality models.

Introduction:

MM5 is a popular and powerful mesoscale meteorological model, now in the public domain and implemented at many sites, that assists improved forecasts of local weather [UCAR, 2002; UW, 2002]. Several groups now incorporate MM5 winds into air-quality models. This is a challenging task, because air pollution is a problem when the winds are light and near the surface, where the physics operate at small scales that MM5 does not well resolve.

This note reports comparisons of wind speeds and directions from MM5 forecasts with surface and upper-air RAWIN data in the Pacific Northwest, with attention to light winds, near the surface. The following sections describe the MM5 model, a reconnaisance comparison with surface meteorological data, and a follow-through that compares MM5 forecasts with RAWIN observations over 17 months at four sites in the Pacific Northwest. It concludes with a discussion, summary, and challenge.

MM5:

The MM5 model is a fifth-generation mesoscale meteorological model originally developed at Pennsylvania State University [Grell, Dudhia, Stauffer, 1995]. For the comparisons of this study the MM5 model at the University of Washington, [UW], was exercised in versions 2.12 and 3.4 with nested horizontal grids [36, 12, 4 km], 33 and 38 vertical layers in terrain-following pressure coordinates, the "MRF" boundary-layer scheme, [Hong and Pan, 1996], and simple parameterizations for radiation and cloud microphysics [Grell, *et. al.*, 1995]. Land-use and topographic information are derived from the 1-km USGS digital database. Initial conditions are taken from the NCEP ETA model, twice daily at 00Z and 12Z [4am and 4pm, PST]. The MM5 model at UW is run in non-hydrostatic mode with forecasts that are posted on the web. For a more complete description of the MM5 domain and implementation at UW, please see the summary article by Mass *et al.* [2003] and the web site referenced as [UW 2002].

Recent studies with MM5 at UW include a description of a regional environmental consortium adapted around operational forecasts with MM5 in the Pacific Northwest [Mass, *et al.*, 2003], an examination of grid-scale effects, [Mass *et al.*, 2002], comparisons with the ETA model [Colle, *et al.*, 2001], a co-evaluation of MM5 with a hydro-meteorological model [Westrick, *et al.*, 2001], and verification of MM5 precipitation [Colle, *et al.*, 2000]. Additional verification statistics can be found on the UW web site [UW, 2002]. A comparison of several mesoscale models with RAWIN and surface observations is reported by Cox *et al.* [1998] for three periods, each of 3-days, in 5 regions. Chock and Kuo [1990] compare trajectories by MM5 with CAPTEX data.

Zhong and Fast [2002] evaluate MM5 with observations and other models during an intensive “VTMX” field campaign in the Salt Lake valley. A rich index of MM5 studies can be found on the web [UCAR, 2002].

Surface Data: A Reconnaisance

As a first look for the present study, 6-hour MM5 wind-speed and direction forecasts by MM5 [version 2.12, exercised with 24-hr forecasts at 4 km grid resolution with wind speeds and directions logarithmicly extrapolated from 40 to 10 meters above the local surfaces and linearly interpolated in latitude and longitude among the four closest grid coordinates of the MM5 model] were compared with 10-meter observations at 00Z [4pm PST], at 96 meteorological sites in Oregon and Washington, for 14 summer and fall days of 1998, as summarized in Table I.

Table I
Comparison of MM5 wind speeds and directions with surface observations
at 96 sites in Washington and Oregon.

Uo = Observed wind speeds, m/s
Um = MM5 wind speeds, m/s
Do = Observed wind directions, degrees
Dm = MM5 wind directions, degrees

N	<Uo-Um>	<<Uo-Um>>	<<1-Um/Uo>>	<Do-Dm>	<<Do-Dm>>	Comment	%
121	-0.07	0.91	27.0 %	-4.1	40.7	2.5 < U <= 5.0	10
222	0.07	1.02	33.9 %	-8.1	44.5	2.0 < U <= 5.0	18
413	0.11	1.03	38.5 %	-7.5	49.5	1.5 < U <= 5.0	34
640	0.07	1.09	55.1 %	-12.1	56.0	1.0 < U <= 5.0	53
904	0.05	1.10	86.0 %	-14.2	62.2	0.5 < U <= 5.0	75
1203	-0.07	1.65	130.0 %	-14.3	62.7	0.0 < U <= 99.0	100

Except when otherwise stated all velocities are m/s, and directions are compass degrees from which the winds are blowing. Single, sharp-brackets < > denote linear averages, and doubled brackets << >> enclose root-mean squares (rms).

The 1st column in Table I lists the number of data pairs with non-default entries for both wind speeds and directions, for both MM5 and surface observations, within the velocity limits specified in column 7 under "Comments".

The 2nd column ,<Uo-Um>, lists the average velocity biases. Note that these are commendably small.

The 3rd column <<Uo-Um>> lists rms differences between modeled and observed wind speeds (m/s). Regrettably, these are not small as can be seen in the 4th column, <<1-Um/Uo>>, which lists their rms relative differences, expressed as percentages. Note that steady-state air-quality models predict tracer concentrations that vary inversely with wind speeds. Thus 50-90% relative uncertainties in estimated wind speeds, as in the red-highlighted 4th and 5th lines of Table I, translate to 2X - 10X uncertainties in modeled tracer concentrations. This is worrisome.

The 5th column, <Do-Dm>, lists the average wind-direction biases, in compass degrees from which the wind was blowing.[1] The negative biases in this column show the MM5 winds to be systematically veered ["clockwise", or "over-geostrophic"] with respect to the observations. This point will be discussed further in a later section of this report.

The sixth column, <<Do-Dm>>, lists the rms differences between the modeled and observed wind directions, in compass degrees. These discrepancies, of 60° or more with wind speeds restricted between 0.5 and 5 m/s, as shown in the red-highlighted 4th and 5th rows of the table, are disturbingly large. Air-quality models exercised with directional uncertainties this large would, for point sources, translate to uncertainties in downwind tracer concentrations, by many orders of magnitude. Concerns over these large directional discrepancies were the driving motivation of this report, and the further comparisons that will be discussed in the following sections.

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[1] Care was taken to account for the discontinuity between 0 and 360 degrees. No |Do-Dm| exceeded 180°.

The 7th column of Table I lists velocity intervals selected for these tests. I have highlighted the 4th and 5th rows as delimiting the spans of most interest to air-quality simulations. Their upper velocity limit [5 m/s ~ 11 mph] is a reasonable bound above which air-pollution near the surface is rarely of concern. Their lower limits [0.5 - 1.0 m/s] were chosen primarily for instrumental reasons: anemometers distributed among the 96 surface sites are a mixture of older and newer types with varying and uncertain precisions at low wind speeds. Note again, please, that comparisons were excluded if any of Uo, Um, Do, or Dm were defaulted or out-of-bounds of the velocity spreads listed in the 7th column of Table I. Specifically, no cases with "0 knot" Uo or Um were included.

The 8th and last column of Table I lists the percentages of observations with both Uo and Um within the specified spans of column 7. Note that the 14 days sampled in this reconnaisance were *not* randomly chosen: 10 were selected as showing the highest noon temperatures at "SeaTac" [Seattle-Tacoma International Airport] during July and August of 1998; the remaining 4 were randomly selected among 30 November days "to keep the others honest". With that caveat, please notice that 53-75% of all 4pm [PST] Uo and Um lay within the velocity bounds of the highlighted rows of Table I. That is, at these 96 sites the fraction of warm summer afternoons with light winds, when urban air-pollution is potentially a problem, is not negligible, and meteorological models to support of air-quality simulations must reasonably be expected account for them.

That said, while these comparisons are certainly disturbing, much of the differences of Table I might reasonably be attributed to very local site effects and instrumental artifacts at the observing sites. To "be fair", and because the MM5 might reasonably be expected to do better at higher altitudes, further comparisons were undertaken with both surface and upper-level wind data, as described in the following sections.

RAWIN Data:

Radio wind soundings [RAWIN] data were assembled from the National Weather Service domestic data stream, through the UNIDATA network, at the four RAWIN sites of Table II, in Washington and Oregon during the 18-month period between August 1, 2000 and January 22, 2002. I am grateful for assistance in this task by Mark Albright and David Ovens, Dept. of Atmospheric Sciences, UW.

Table II

RAWIN Sites

Lat	Lng	Z(mASL)	State	Name	site	codes
42.3742	122.8735	405	OR	Medford	MFR	72597
47.9371	124.5612	97	WA	Quillayute	UIL	72797
44.9095	123.0025	64	OR	Salem	SLE	72694
47.6199	117.5338	728	WA	Spokane	OTX	72786

RAWIN data are reported in integer knots [0, 1, 2, 3, ..][2] and wind-direction bins of 5 degrees [000, 005, ...]. Histograms of the wind-speed distributions appear smooth and "sensible", with no obvious binning errors, except that the "0" bins may be somewhat overpopulated, presumably at the expense of the next higher bin at 1 knot.
In all of the comparisons that follow, data pairs were rejected when the observed RAWIN velocities were less than 1 knot [0.51 m/s][3]. Later sections of this note discuss some effects of binning errors.

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[2] Integer knots were converted in this study to m/s [1 knot = 0.5148 m/s], into "bins" of 0.00, 0.51, 1.03, 1.54, ... m/s. These canonical speeds are assumed to denote the bin centers. Thus "0.51" is presumed to span roughly between $0.26 < U < 0.76$ m/s.

[3] Thus 1-knot RAWINDS were included. To avoid a bias error, comparisons with MM5 wind speeds less than 0.5 m/s were retained, as long as the RAWIN speeds exceeded 0.5 m/s.

For the present study the MM5 model was exercised with 4 km grid resolution, separately initialized at 12, 24, and 36 hours before comparisons with RAWIN observations at 00Z and 12Z [4am and 4pm, PST]. At UW, as elsewhere, the MM5 model is "work in progress", with changes made from time to time for research, and as computational facilities improve. A significant upgrade was installed on July 9, 2001, from MM5 version 2.12 to 3.4, with an increase from 33 to 38 vertical layers. Some effects of this are discussed below. All together, the present data contain 103,541 non-default comparisons of contemporary wind speeds and directions from both MM5 and RAWIN observations.

Comparisons and Scores:

Tables III.1 and III.2 summarize comparisons between MM5 winds and RAWIN observations. As with those of Table I, the MM5 wind speeds, Um, and directions, Dm, were linearly interpolated by latitude and longitude to match the locations of the RAWIN sites listed in Table II. Additionally, the "surface" MM5 winds were logarithmically extrapolated from the lowest MM5 levels [32 and 19 meters, respectively, for versions 2.12 and 3.4] to 10 meters above the local surfaces, whose elevations above sea-level are listed also in Table II. As with Table I, singled sharp brackets < > denote linear averages, and doubled brackets << >> are root- mean-squares. Pressure levels are millibars [mb], except that “Surf” arbitrarily refers to the lowest reported pressure level at the individual RAWIN sites.

The rightmost columns in Tables III.1 and III.2 contain "Coefficients of Determination", $\boldsymbol{R}^2$, defined as:

$$\boldsymbol{R}^2 = 1 - \Sigma[(\boldsymbol{U}\text{o}-\boldsymbol{U}\text{m})^2 + (\boldsymbol{V}\text{o}-\boldsymbol{V}\text{m})^2] \;/\; \Sigma[(\boldsymbol{U}\text{o}-<\boldsymbol{U}\text{o}>)^2 + (\boldsymbol{V}\text{o}-<\boldsymbol{V}\text{o}>)^2] \qquad [1]$$

In equation [1] $\boldsymbol{U}$o and $\boldsymbol{V}$o are the x- and y-projections of the observed wind vectors (m/s), and <$\boldsymbol{U}$o> and <$\boldsymbol{V}$o> are the averages of $\boldsymbol{U}$o and $\boldsymbol{V}$o, that is, the x- and y- projections of "climatological" wind vectors (m/s). The two sums in equation [1] may be thought of as the sum of areas of circles drawn with radii equal to the distances between endpoints of the observed and modeled wind vectors, and the similar areas of circles with radii equal to the distances between endpoints of the observed and climatological winds. Note that there may some confusion between “R^2” and “r^2”, the square of Pearson’s correlation coefficient. The latter is always positive, but R^2 may be negative if the “predictands” [Um, Vm] are less skillful than “climatology”, [<Uo>, <Vo>].

Please take a minute to look at these tables and figures, on the next and following pages.

Summarizing briefly:

1. The MM5 does very well, with $\boldsymbol{R}^2$ scores up to a remarkable 0.91, when the wind speeds exceed 5 m/s, at altitudes above 1 km. [Figure 1 (next page) and Table III.2, last column, green highlight.]

2. The MM5 does very poorly at wind speeds in the range 0.5 < Uo < 5 m/s [1-11 mph], with $\boldsymbol{R}^2$ scores less than zero [worse than climatology] **at all levels**. [Figure 1 and Table III.3, last column, red highlight.]

3. With all data the wind-speed biases <Uo-Um> trend from +0.8 to -1.1 m/s, decreasing with altitude. [Table III.1, column 5]. Wind-speed bias ratios, <Um/Uo>, are close to unity when the observed speeds exceed 5 m/s , but range from 1.6 to 2.0 when 0.5 < |U| < 5 m/s [Figure 2a,b (next page) and Table III.3, column 6, orange highlight], **at all altitudes**, with no obvious trend.

4. Wind-direction biases, <Do-Dm>, range up to 15 degrees, in most cases with Dm > Do. That is, the modeled winds blow preferentially from a more clockwise direction ["veered", or "over-geostrophic"] than is observed. [Figure 2a and Tables III.1-III.3, columns 8, purple highlight.]

5. RMS velocity differences, <<Uo-Um>>, commonly range between 2 and 5 m/s, and are comparable to, or exceed, the average speeds, <Uo>, when the winds are light, at all levels [Figure 1b and Table III.3, columns 4 and 7].

6. RMS direction differences, <<Do-Dm>> range up to 74 degrees, with larger numbers at lower levels and wind speeds. [Figure 2b and Table III.3, column 9, blue highlight]

Table III.1
Comparisons between MM5 and observed RAWIN wind speeds and directions.
All data between Aug. 1, 2000 and Jan 22, 2002
Observed wind speeds, Uo, **greater than 0.5 m/s**.

Pres	Z	Npts	<Uo>	<Uo-Um>	<Um/Uo>	<<Uo-Um>>	<Do-Dm>	<<Do-Dm>>	R^2
mb	km	....	m/s	m/s	....	RMSm/s	degrees	RMSdeg	....
150	13.40	3643	20.33	0.78	1.01	4.51	-2.12	17.53	0.78
200	11.58	3711	26.14	0.85	1.00	4.78	-1.19	14.86	0.89
300	8.94	3901	27.66	0.59	1.02	4.99	0.14	16.46	0.91
400	6.95	3985	22.59	0.26	1.04	4.27	0.01	17.82	0.90
500	5.33	4020	18.11	0.35	1.04	3.70	-0.89	20.63	0.88
700	2.73	4017	11.08	0.25	1.07	3.20	-2.28	28.11	0.75
850	1.17	3941	6.96	-0.61	1.31	3.14	-10.55	42.87	0.50
925	0.60	2918	5.80	-1.07	1.51	3.14	-9.90	53.39	0.37
Surf	0.03	3433	3.42	-1.12	1.65	2.54	-14.89	67.52	-0.56

Table III.2
Comparisons between MM5 and observed RAWIN wind speeds and directions.
All data between Aug. 1, 2000 and Jan 22, 2002
Observed wind speeds, Uo, **greater than 5.0 m/s.**

Pres	Z	Npts	<Uo>	<Uo-Um>	<Um/Uo>	{Uo-Um}	<Do-Dm>	{Do-Dm}	R^2
mb	km	....	m/s	m/s	....	RMSm/s	degrees	RMSdeg	....
150	13.40	3577	20.64	0.84	1.00	4.51	-1.99	15.79	0.78
200	11.58	3650	26.51	0.90	0.99	4.80	-0.99	13.00	0.89
300	8.94	3823	28.16	0.64	1.00	5.01	0.06	14.26	0.91
400	6.95	3868	23.18	0.33	1.01	4.29	-0.08	15.16	0.91
500	5.33	3822	18.89	0.44	1.00	3.74	-0.48	15.80	0.89
700	2.73	3427	12.43	0.51	0.98	3.30	-1.71	20.13	0.78
850	1.17	2266	9.89	-0.08	1.02	3.50	-8.60	26.87	0.64
925	0.60	1333	9.53	-0.51	1.07	3.21	-8.90	28.07	0.62
Surf	0.03	696	6.87	-0.22	1.06	2.83	-11.93	34.07	0.10

Table III.3
Comparisons between MM5 and observed RAWIN wind speeds and directions.
All data between Aug. 1, 2000 and Jan 22, 2002
Observed wind speeds in the range **$0.5 < |U| \le 5.0$ m/s.**

Pres mb	Z km	Npts	<Uo> m/s	<Uo-Um> m/s	<Um/Uo>	<<Uo-Um>> RMSm/s	<Do-Dm> degrees	<<Do-Dm>> RMSdeg	R^2 ....
150	13.40	66	3.49	-2.71	1.90	4.22	-8.83	58.81	-6.92
200	11.58	61	3.54	-1.76	1.60	3.35	-13.24	57.63	-4.93
300	8.94	78	3.21	-2.05	1.86	3.86	3.78	59.86	-4.89
400	6.95	117	3.09	-1.98	2.03	3.76	2.77	56.70	-4.12
500	5.33	198	3.19	-1.46	1.77	2.98	-8.83	61.86	-3.01
700	2.73	590	3.24	-1.29	1.57	2.61	-5.59	55.01	-0.70
850	1.17	1675	2.99	-1.32	1.69	2.57	-13.19	57.86	-0.59
925	0.60	1585	2.67	-1.53	1.88	3.09	-10.74	67.72	-1.50
Surf	0.03	2737	2.55	-1.35	1.80	2.46	-15.65	73.65	-1.25

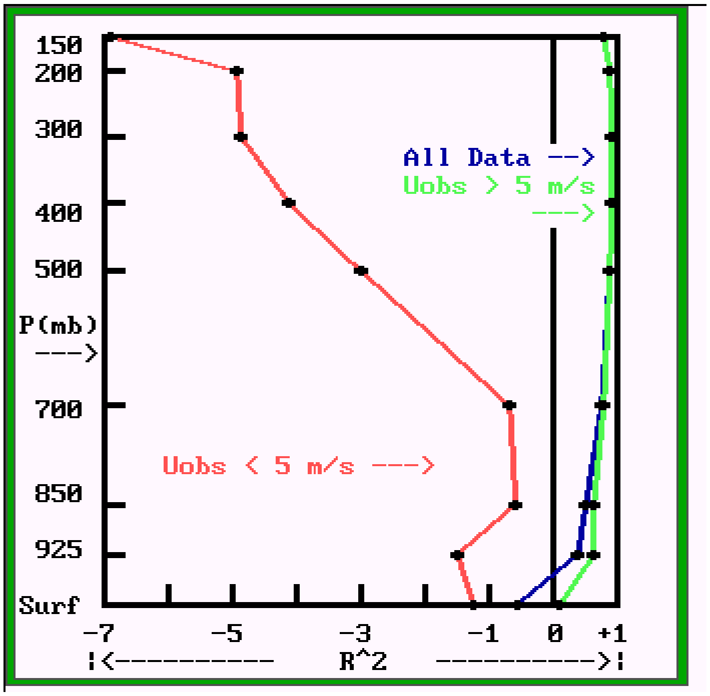

Figure 1

R^2 scores as functions of pressure-heights and wind-speed classes.

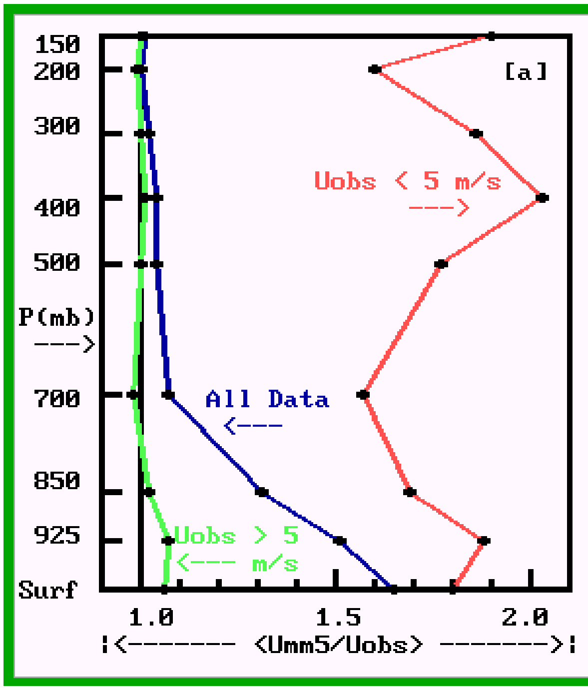

Figure 2a
<Um/Uo> as functions of pressure-heights and observed wind-speed classes.

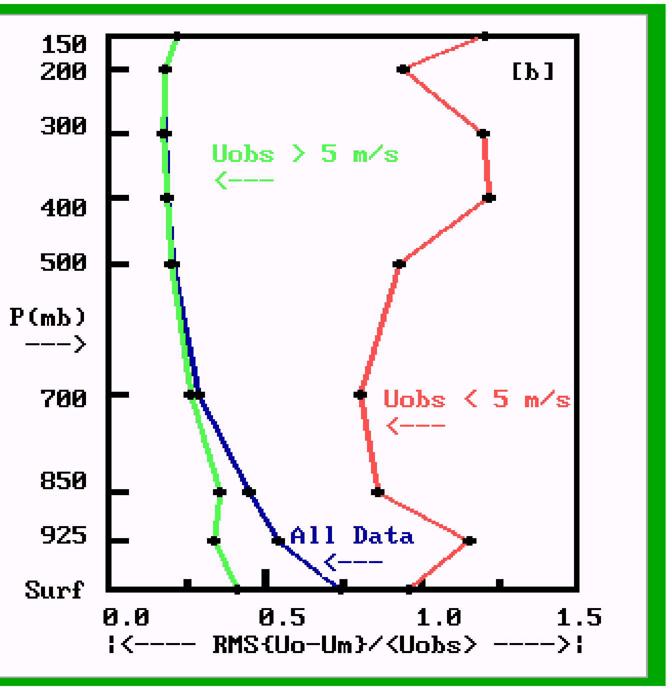

Figure 2b
<<Uo-Um>> as functions of pressure-heights and observed wind-speed classes.

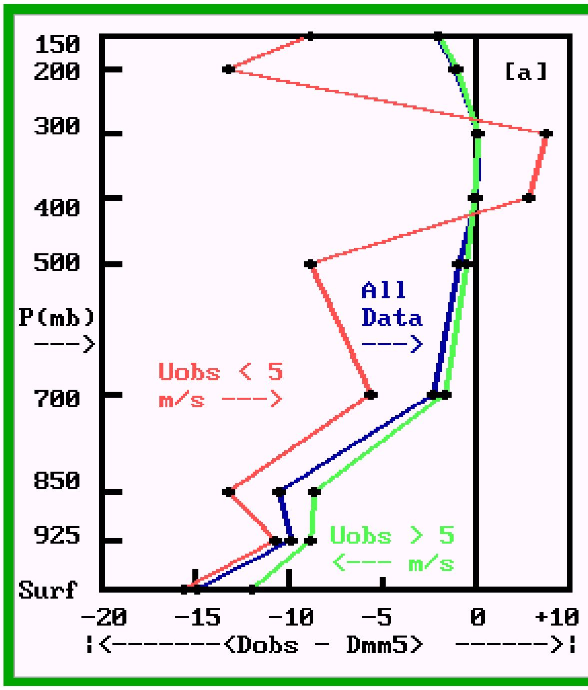

Figure 2a
Average wind-direction bias, degrees, <Dobs-Dmm5> as functions of pressure-heights and wind-peed classes

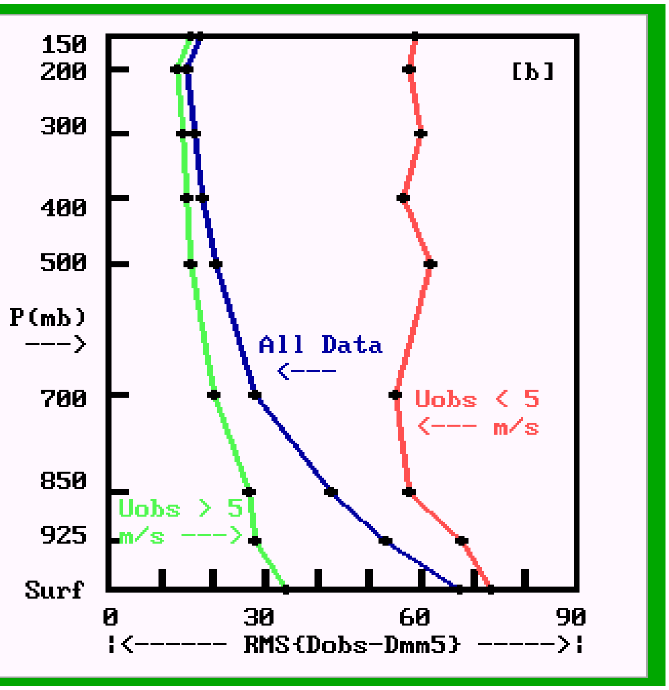

Figure 2b
Root-Mean-Square wind-direction differences, degrees, as functions of pressure-heights and wind-speeds

In Tables III.1-3 and elsewhere in this text, the climatological winds were computed at every height, every month, and every site, but were ***not*** segregated by time of day [00Z or 12Z]. Table IV gives a compressed summary of the R^2 scores, by sites and wind-speed intervals, averaged over heights [weighted by pressure increments and numbers of observations], and months [weighted uniformly]. "Grand-Average" scores, **<R^2>**, for "AllSites", the rightmost columns of Table IV, are also weighted uniformly.

Table IV

Summaries of R^2 scores, by sites and wind-speeds.

ALL Data. Initialized at -12 hrs.

	|<-------------		R^2 SCORES	-------------------	>|
Winds	MEDFORD	QUILLAYUTE	SALEM	SPOKANE	AllSites
$0.5 < \|U\| \leq 99$ m/s	0.37	0.71	0.73	0.63	<0.67>
$5.0 < \|U\| \leq 99$ m/s	0.74	0.84	0.83	0.78	0.82
$0.5 < \|U\| \leq 5$ m/s	-2.13	-1.05	-0.45	-0.93	-1.11

For discussion in this note the **<R^2>** score for "AllSites" and "all winds" [$0.5 < |U| \leq 99$ m/s], [the upper-right entry of Tables IV, emphasized here with blue highlight and elsewhere by angled brackets, <>], is proposed as a useful, single "best" score of MM5.

Discussion:

Perhaps the first thing to notice is that the rms velocity and directional differences reported with MM5 and RAWIN data at the surface with light-wind cases in Table III.3 are consistent with those of the earlier reconnaisance with 10-meter data from the 96 meteorological sites, as reported above in Table I. Thus it appears that those former differences may not be dismissed as owing largely to local artifacts of poorly sited wind vanes and anemometers.

Continuing, and repeating for this discussion, the definition of R^2, or "Coefficient of Determination" is

$$R^2 = 1 - \Sigma[(U\text{o}-U\text{m})^2+(V\text{o}-V\text{m})^2] / \Sigma[(U\text{o}-<U\text{o}>^2 + (V\text{o}-<V\text{o}>)^2] \qquad [1]$$

In equation [1] ***U***o,***V***o, ***U***m,***V***m, and <***Uo***>,<***V***o> are the x- and y-projections of the observed, modeled, and climatological wind vectors. The numerator on the right-hand side of equation [1] may be thought of as the sum of the areas of error circles around the end points of the modeled wind vectors, centered on the observations, and the denominator as the sum of areas of error circles centered about the end points of the averaged, or "climatological" wind vectors.

With perfect models and predictions, all ***U***o equal ***U***m, all ***V***o equal ***V***m, and the R^2 scores would be identically equal to unity. If for every modeled prediction, [***U***m,***V***m], one were to substitute instead the climatological winds, [<***U***o>,<***V***o>], then R^2 scores would be identically zero. Thus the extent to which R^2 exceeds zero is a measure of "improvement above climatology". With current models, typical R^2 are about 0.9 for 24-hour predictions of the heights of 500 mb geopotential surfaces at specified locations. Typical R^2 for "this-afternoon" predictions of air-tracer concentrations at specified locations are about 0.4. Typical R^2 for 24-hr predictions of rainfall accumulations are about 0.2.

All modelers encounter embarrassing cases with R^2 less than zero, that is, where our models are less skillful than the "Farmers' Almanac", but we do not commonly report them.

The present example is an interesting case where, with 12-hour forecasts, the MM5 model does very well [$R^2 = 0.91$] in part of its domain [$5.0 < |U| \leq 99$ m/s in the middle troposphere; Figure 3 and Table III.2, last column], but very poorly [$\boldsymbol{R}^2 \ll 0$] with wind speeds below 5 m/s, at all altitudes[4] [Figure 3 and Table III.3, last column]. This is disappointing, but it is still useful to know, both to focus our attention where we must work for improvements, and where we must be cautious not to apply the MM5 model outside its valid domain.

Near the surface at all four sites the most probable RAWIN velocity [the "mode" of the probability distribution functions, pdfs, excluding zeros] was 2.06 m/s [4 knots]. Medford is anomalous, however, with 78% of all reported near-surface winds at this speed and below, compared with 33-35% at the other three sites. The **$<\boldsymbol{R}^2>$** scores at Medford are for this reason significantly lower than at Quillayute, Salem, and Spokane [Table IV].

On July 9th of 2001 an MM5 version upgrade was installed at UW, from v2.12 to v3.4. At that time the domain boundaries were shifted slightly, and the number of vertical levels increased from 33 to 38, with added levels near the surface. It is interesting to ask whether this shift was accompanied by a perceptible increase in predictive skill.

With the months of February through June omitted from the first period, to match the missing data in the second, the "AllSites" **$<\boldsymbol{R}^2>$** scores of the two periods were 0.60 and 0.68, respectively, a noticeable improvement of v3.4 over v2.12. If the climates of the two periods were identical, then sampling fluctuations and binning errors would be expected to produce uncertainties in **$<\boldsymbol{R}^2>$** that were less than ±0.01. In the real case, however, with year-to-year climate jitter, estimating the significance of the **$<\boldsymbol{R}^2>$** differences is difficult and uncertain, owing to unmeasured climate fluctuations that occur at all frequencies. The RMS of observed variations of the monthly $\boldsymbol{R}^2$, among the four sites, is ≈ ± 0.07. With 7 monthly averages contributing to each score, the standard errors in **$<\boldsymbol{R}^2>$** are ≈ ±0.03, and the one-sigma confidence interval for a difference [v3.4 – v2.12] is ≈ ±0.04. By this approximate test an improvement between v2.12 and v3.4 appears to be significant with better than one-sigma confidence[5]. This is gratifying, and it is nice to know that we can detect **$<\boldsymbol{R}^2>$** improvements of this magnitude with data records of a year or less.

With the MM5 initialized at -12 , -24 and -36 hours, respectively, before comparisons with RAWIN observations, a noticeable fall-off of **$<\boldsymbol{R}^2>$** scores is observed, from 0.67 to 0.61 to 0.54. This decay of skill implies a characteristic predictive persistence time of about 110 hours, or 4.6 days.

At these four northwest sites, wind speeds less than 5 m/s are observed over half the time at 850 mb [1.2 km], over two thirds at 925 mb [0.6 km], and 80% of hours [at 00Z and 12Z] at the surface. The probability distribution functions [pdfs] of [Uo-Um] and [Vo-Vm] are approximately Gaussian, centered about their means, <Uo-Um> and <Vo-Vm>. The probabilities of various exceedances can therefore be calculated from standard tables, and similarly with [Dm-Do] when the wind speeds exceed 5 m/s. When the winds are light, however, the pdf of the directional differences differs significantly from Gaussian. With observed wind speeds less than 5 m/s, wind-direction errors exceed 30 degrees about half the time, 90 degrees about a fifth of the time, and 165 [!] degrees about 15% of the time. These errors vary little with the pressure levels, which suggests that timing errors may be more limiting than surface effects.

Not surprisingly, the MM5 does a bit better at these four sites during the local afternoons **[$<\boldsymbol{R}^2>$** = 0.67, when the winds are stronger] than in early mornings [$<\boldsymbol{R}^2>$ =0.59, with lighter winds][6].

Near the surface the MM5 at UW shows a net positive velocity bias of about 2 m/s and net "over-geostrophic" wind directions of about 15 degrees. [Tables III.1,2,3]. Both are consistent with underestimating the near surface drag. In MM5 that drag is modeled with a variant of Monin-Obhukhov similarity theory, and parameterized as a function of a "roughness length", Zo, that is assumed to be a static property of the local surface. With MM5 at UW, those Zo's are estimated semi-empirically, at every 4km by 4km grid square, as functions of land-use and topography,

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[4] Actually, the MM5 does worse than substituting *zero* winds, when $0.5 < |U| \leq 5$ m/s, at all altitudes [!].

[5] Strictly, Pearson's transform with $\chi 2$ tests would be preferred. Using the month-to-month variations to estimate climate fluctuations qualitative only.

[6] In this case, only, the climatologies were computed separately for 00Z and 12Z.

with no value exceeding 0.5 meters. The present study suggests that at UW the MM5 systematically underestimates low-level drag.[7]

The RAWIN data are reported after roundoff into bins with integer wind speeds [knots] and five-degree compass angles. Effects of binning on the precisions of **<R^2>** scores can be explored by adding intentional random noise to the observed wind speeds and directions, uniformly distributed between $-0.5 < U \leq +0.5$ m/s, and $-2.5 < Do \leq +2.5$ degrees. Degrading the data in this way affected the **<R^2>** scores in the right column of Table IV only in the case with $0.5 < U < 5.0$ m/s, by +0.01.

RAWIN observations are also vulnerable to both random and systematic errors that are likely high near the surface with light winds. It is for this reason that data pairs with observed wind speeds less than 0.5 m/s have so far been omitted. Other low-cutoff thresholds give higher **<R^2>** scores: for example **<R^2>** = 0.76 with $3.0 < U < 99$ m/s, and **<R^2>** = 0.56 with $3.0 < U < 5$ m/s. In the light-wind case the R^2 scores remain negative at all altitudes.[8]

Competent persons close to MM5 attest to its real assistance to skilled weather forecasting. Attention to the applicability of MM5 for air-quality modeling has been a little slow, however, and these poor scores at low wind speeds are disturbing. It is natural to suggest that they are in some degree “not fair”. A reasonable objection to the variance and R^2 scores reported here is that both the surface and RAWIN data capture high frequency variance that is brief and local, while the MM5 smoothes over larger scales of both space and time. This is undeniably true.

For several reasons, however, these present comparisons remain disturbing:

> Note that discrepancies between RAWIN and MM5 wind speeds and directions cannot easily be reconciled as resulting from differences in sampling intervals, only. If two tracer particles were to start at the same point, one following an hourly-averaged MM5 wind vector [Um, 0] and the other a wiggly path terminating at the same end-point, then random short samples of $[(Uo)^2 + (Vo)^2]^{1/2}$ along the indirect trajectory must necessarily average to higher wind speeds than Um[9] . But the observations contradict this [Table III.3, column 5.]
>
> Both lateral and vertical dispersions of air-quality tracers are sensitive to .. and indeed are driven by .. short-term variances in wind speeds and directions. Any mesoscale meteorological model supporting air-quality simulations may reasonably be asked to account for short-period variances also.
>
> The MM5 model is initialized in a somewhat circular recipe using both surface and RAWIN observations that have been filtered, weighted, and rationalized in a self-consistent way with the assistance of *another* meteorological model[10] . Thus challenging either surface or RAWIN data as *systematically* wrong leads inescapably to challenging the initial conditions used by MM5.

Yes, comparisons of models with observations should also be attempted with data smoothed to similar scales. Unfortunately, adequate data are not now available to make such comparisons. They do in principle exist, however, with RASS[11] sounders, which permit *a posteriori* smoothing, at least in time. [Spatial smoothing is implicit also, but is not an independent variable, as it depends on wind speeds.] A good project would be to harvest RASS data for a comparison exercise similar to the present one.

A supportive argument for mesoscale models generally is that with bigger and faster computers we may soon expect significant improvements from better algorithms and finer spatial resolution. This is reasonable, and the present

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[7] Boundary-layer purists object on theoretical grounds to Zo much greater than 0.5 meters. Empirically, Zo’s ≈ 2 m appear necessary for an “engineering fix”.

[8] The climotological winds were also averaged with cut-off below 3 m/s.

[9] By about a factor of two, if <<Do-Dm>> ~ 60 degrees, as in Table lII.3, column 9.

[10] [see: <http://www.ecmwf.int/products/forecasts/guide/The_4DVAR_analysis_procedure.html> and references cited therein.

[11] “RASS” is an acronym for Radio-Acoustic Sounding System. These powerful and expensive instruments return continuous profiles of wind speeds and directions up to altitudes of several kilometers. Two RASS profilers now operate in Washington State.

study will ... one hopes ... date itself fairly rapidly. Two observations argue for caution, however: with MM5 at UW the RMS velocity and direction errors diminish only slowly when the model is progressively exercised with grid resolutions of 36, 12, and 4 km [UW, 2002], and light-wind performance does ***not*** improve with height above the surface, as one would expect if topography were dominating [Figure 3 and Table III.3, columns 4-10].

Is MM5 good enough for air-quality models?

Each user must decide. Here are some points to consider.

1. Air pollution lives near the ground at low wind speeds, where MM5 does least well.

2. We may soon hope for implementations of mesoscale meteorological models with reduced mean biases and rms discrepancies in wind speeds and directions, but cautious users should check with the modelers to assure [and insist!] that these have been achieved, and verified.

3. Both horizontal and vertical dispersion times of mesoscale-averaged air-tracer concentrations vary roughly with the inverse of wind speeds. Thus a 2.46 m/s rms wind-speed uncertainty [Table III.3, 7th column, last row] in the presence of a "true" wind speed of 4 m/s [the mode at these four RAWIN sites] would be expected to generate uncertainties of 2X or more in derived tracer concentrations.

4. Applications requiring predictions of targeted trajectories would appear to be incompatible with rms wind-direction uncertainties near 70 degrees [Table III.3, 9th column, last row.]

5. An argument can be forwarded that longer-term "climate" models using MM5 winds might acceptably average over shorter-term directional errors. It is not clear, however, whether this would offer advantages over the simpler use of climatological winds, if they are available.

Summary:

MM5 does remarkably well [$R^2 > 0.9$] the middle troposphere when the winds exceed 5 m/s. It does poorly [$R^2 < 0$] at all levels when wind speeds are less than 5 m/s, which occur in 80% of all hours near the surface at the four RAWIN sites of this study.

It is not clear that MM5 may usefully assist air-quality modeling in light winds, near the surface.

A Challenge:

Come on, Fellas! We *gotta* do better than climatology!

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