Upper-Troposphere MM5 and WRF Temperature Error and Vertical Velocity Coupling

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ABSTRACT

The fifth-generation Pennsylvania State University–National Center for Atmospheric Research Mesoscale Model (MM5) and the Weather Research and Forecasting Model (WRF) have been employed to predict troposphere temperatures for atmospheric study and operational decision making with positive results. Temperature bias in MM5 and WRF has been noted in previous troposphere studies through radiosonde vertical profile comparison; however, long-range horizontal in situ temperature observations have never been utilized to assess MM5 and WRF upper-troposphere temperature prediction. This study investigates upper-troposphere temperature forecasting of MM5 and WRF utilizing long-range in situ observations linking temperature error to forecast vertical velocity within the upper troposphere over surface elevation changes and different surface types. Temperature observations were taken during flights over North America, Europe, and southwest Asia between 6000 and 7600 m above sea level and compared with MM5 and WRF upper-troposphere forecasts. Regression analysis indicated MM5 and WRF upper-troposphere temperature forecast errors were related to changes in forecast vertical velocities within 100 km laterally of the modeled flight tracks between 39° and 59°N latitude. Temperature error and forecast vertical velocity coupling occurred in MM5 and WRF forecasts over land, while no evidence of temperature error and forecast vertical velocity coupling in MM5 or WRF forecasts was found over water. Evaluation of MM5 and WRF forecasts displayed varying results of temperature error and forecast vertical velocity coupling between specific surface elevations above sea level, vegetative cover, and urban influences.

1. Introduction

a. Background

Atmospheric temperature prediction has improved escalating atmospheric modeling skill and provided high degrees of success in regional climate modeling. Prior to computer modeling, weather prediction methods utilized manual calculations to solve lengthy mathematical formulas forecasting atmospheric temperature on which to base operational decisions (i.e., optimal aircraft cruise altitude) (Zhu et al. 2002). Advancements in computer technology allow atmospheric models to quickly calculate atmospheric temperatures and rapidly assimilate sounding data, improving the skill of meteorological predictions (Ali 2004). Computer technology improvements in atmospheric model computations (i.e., processor speed) require continued testing and validation to ensure atmospheric temperature modeling skill is not degraded (Cheng and Steenburgh 2005; Knutti et al. 2010). Therefore, atmospheric temperature forecasts require comparison with in situ temperature measurements and other modeled physical parameters (i.e., forecast vertical velocity) to determine if temperature errors are exhibited in model prediction (Manning and Davis 1997).

Atmospheric model developments utilizing improved computer processing have introduced models such as the fifth-generation Pennsylvania State University–National Center for Atmospheric Research Mesoscale Model (MM5) described by Grell et al. (1994), replacing time-consuming manual statistical computations exhibited by Cornett and Randerson (1977). The MM5 has enhanced lower-troposphere and stratosphere temperature prediction by utilizing model-to-model comparisons, in situ aircraft and radiosonde measurements exhibited in regional meteorological investigation by Chandrasekar et al. (2002), boundary layer study by Song et al. (2004), and tropical cyclone analysis by Pattanayak and Mohanty (2008). MM5 has been used in Antarctica to compare...
forecast temperature and radiosonde soundings from the surface to 700 hPa by Guo et al. (2003), aircraft and radiosonde soundings up to 400 m AGL in Greenland katabatic layer studies by Bromwich et al. (2001), and short-range forecast skill in the northeast United States by comparing model and observation network temperatures within 2 m AGL by Jones et al. (2007). Research using MM5 has provided insight into regional atmospheric temperature prediction from the surface to 700 hPa by identifying varying MM5 temperature forecast skill by each study. However, to our knowledge there has been no study addressing the upper-troposphere temperature forecasting capabilities of MM5.

With MM5 successfully used as a forecasting tool in the lower troposphere, the Weather Research and Forecasting Model (WRF) described by Skamarock et al. (2008) and discussed by Zhang et al. (2009) has been developed as a replacement for MM5. Previous WRF forecast assessments have proved comparable to MM5 with improved capability of rapid data assimilation and nudging in WRF allowing improvements in model skill over MM5 (Pattanayak and Mohanty 2008; Wang et al. 2008). Improved assimilation of in situ measurements and radiosonde soundings suggest WRF skill within the troposphere has improved prediction of future temperature conditions over populated areas such New England and western Europe (Hines and Bromwich 2008; Coniglio et al. 2010; Wilson et al. 2011, 2012). For unpopulated regions where assimilation data are sparse and no upper-atmospheric temperature measurements exist (i.e., Atlantic Ocean and southwest Asia), little evaluation of WRF upper-troposphere temperature prediction has been accomplished, suggesting an unverified condition of WRF temperature modeling (Cardinali and Isaksen 2003). For this reason, WRF upper-troposphere temperature forecasts require exploration to identify anomalies in upper-troposphere temperature prediction that may go undetected.

b. Motivation

To use MM5 and WRF forecasts with confidence, the capability to predict temperature within the upper troposphere requires thorough validation encompassing regions without radiosonde capability or frequent aircraft travel. MM5 and WRF are applied in areas where temperature biasing might place upper-troposphere forecast users (i.e., aircraft flight planners) in a vulnerable position (i.e., selection of aircraft cruise altitudes). Vulnerabilities to the upper-troposphere forecast user may include erroneous areas of turbulence or incorrect cloud moisture prediction resulting in unexpected ice accumulation on aircraft control surfaces, reducing safety for crew and passengers (Zhu et al. 2002). Scenarios similar to these must be reduced in order for upper-troposphere prediction users to safely alleviate unnecessary aircraft operating expenses and eliminate the potential for aircraft loss (Mass 2006). To assist in this goal, MM5 and WRF temperature forecasting was explored across the upper troposphere to include areas of sparse radiosonde or aircraft in situ measurement data since temperature is a key variable in calculations used to predict other physical parameters such as cloud development and vertical motion of the atmosphere.

This study began with operational testing of MM5 and WRF upper-troposphere forecasts for worldwide use by aircraft to identify any temperature forecast anomalies that may exist. Operational testing was accomplished on a series of transworld flights within the upper troposphere using predesignated flight routes between 39° and 59°N latitude. MM5 and WRF upper-troposphere multileg vertical cross-sectional temperature and vertical velocity forecasts were obtained prior to observation flights where upper-troposphere temperatures were recorded from aircraft navigation system displays by flight crews. MM5 and WRF temperature errors (i.e., difference between forecast and observed temperature) were determined and RMSE computed, yielding an RMSE of 1.8°C (Fig. 1). The RMSE of 1.8°C was initially thought to have been due to lateral distance deviation of the aircraft from the MM5 and WRF modeled flight tracks as a result of required course deviations by air traffic control or hazardous weather avoidance.

A correlation test was accomplished between upper-troposphere combined MM5 and WRF temperature error and lateral distance deviation from the modeled flight tracks producing a correlation coefficient R of 0.1, suggesting lateral distance deviation was not the prime contributor to the temperature RMSE and indicating another cause (Fig. 2). MM5 and WRF upper-troposphere temperature errors were plotted in time series producing
a similar signature as MM5 and WRF upper-troposphere forecast vertical velocity (Fig. 3). The similarity in signature between MM5 and WRF upper-troposphere temperature error and forecast vertical velocity prompted a correlation test producing an $R = 0.4$. An $R = 0.4$ suggests a relationship between MM5 and WRF upper-troposphere temperature error and forecast vertical velocity providing the motivation for this study and attempting to answer the following question:

1) Is temperature error and forecast vertical velocity coupling an anomaly in MM5 and WRF upper-troposphere temperature forecasts?

Further examination of MM5 and WRF upper-troposphere temperature error (Fig. 1) suggests a variation of temperature error within 100 km of lateral distance deviation from modeled flight tracks between 39° and 59°N, leading to the following question:

2) Is there a lateral distance deviation from upper-troposphere MM5 or WRF modeled tracks where temperature error and forecast vertical velocity coupling diminishes?

Additionally, studies on land–atmosphere coupling and land-cover changes affecting heat flux by Evans and Geerken (2004), Giorgi (2006), Sheffield and Wood (2008), Pitman et al. (2009), Myoung et al. (2012), de Noblet-Ducoudré et al. (2012), and Boisier et al. (2012) prompted the following question:

3) Is temperature error and forecast vertical velocity coupling in MM5 and WRF upper-troposphere temperature forecast related to or enhanced by geographical traits such as changes in surface elevation above sea level or surface types such as land, water, urban influences, or vegetation?

RMSE and regression analysis was performed on MM5 and WRF upper-troposphere temperature error data indicating associations between temperature error and forecast vertical velocity over different surface elevations above sea level and surface types such as land, water, urban, and vegetation (Jolliffe 2007). Evaluation of these parameters at upper-troposphere levels provided insight into an MM5 and WRF model anomaly shedding light into MM5 and WRF upper-troposphere temperature forecast performance (Cocke et al. 2006).

2. Experiment design

a. Methodology overview

MM5 and WRF upper-troposphere temperature and vertical velocity forecasts were provided by the U.S. Air Force Weather Agency (AFWA) and temperature observations were taken using aircraft navigation systems during long-range cruise flights in the upper troposphere. Aircraft navigation system–displayed temperature was recorded by the flight crew and compared to MM5 and WRF forecast temperature to determine temperature error. Aircraft observation and radiosonde temperatures were compared when available ensuring anomalies were not present in aircraft systems, which could corrupt model testing. Datasets were stratified and tested utilizing RMSE and regression analysis to identify statistically significant temperature error and vertical velocity coupling relationships. Statistically significant data were tested to a 95% confidence interval confirming temperature error and vertical velocity coupling relationships in MM5 and WRF upper-troposphere forecasts.

b. Temperature observation collection

Aircraft type selection was critical to best accomplish upper-troposphere temperature observations (Cardinali
et al. 2004; Wroblewski et al. 2010). Larger jet aircraft were unfavorable because of cruise altitudes above upper-troposphere levels, while smaller aircraft were unable to operate at the distances required for long-range observations (Moninger et al. 2003). Aircraft availability was considered, requiring upper-troposphere temperature observations to be accomplished concurrent with an already designated flight, easing the selection process. The aircraft of choice was the C-130 Hercules, which met all requirements of cruise altitude, observation recording feasibility, distance capability, and availability. The aircraft was provided with Wyoming Air National Guard cooperation and was supported by 187th Airlift Squadron flight crews.

Atmospheric temperature was provided by a single Goodrich 102A external probe mounted on the aircraft fuselage feeding data to the aircraft air data computer (ADC) and the total air temperature gauge (Goodrich Sensor Systems 2002a). The probe integrates protection against inlet blockage from dust, insects, or bird strikes and provides thermal protection to prevent inlet blockage from ice formation without degrading accuracy (Goodrich Sensor Systems 2002b). Total air temperature compressibility correction factors were applied to C-130 temperature gauge observations per aircraft operating procedures in agreement with findings by Khelif et al. (1999). Once aircraft capability was identified and found to be satisfactory, a spreadsheet for manual in-flight data recording was developed using Microsoft Excel. Upper-troposphere temperature data collection was then accomplished on predesignated flights while established at cruise altitude, reducing ADC and navigation solution errors by aircraft climb or descent (Cole and Jardin 2000).

Upper-troposphere temperature observations took place on one transoceanic and three transcontinental flights in February 2009 and three transcontinental flights in April 2009 between 39° and 59°N, totaling seven separate observation datasets. Upper-troposphere temperature observations were manually recorded in flight from aircraft navigation system displays and total air temperature gauge readings \( T_G \) between 6000 and 7600 m above sea level every 5 min, resulting in 25-km intervals. Data recording included universal coordinated time (UTC), observation geographical coordinates, aircraft altimeter, \( T_G \), and aircraft navigation system–displayed ambient air temperature. Compressibility at the temperature probe intake required a correction factor of \(-10^\circ\text{C} \) [Eq. (1)] (U.S. Air Force 2006) to all \( T_G \) readings. \( T_G \) readings are observed upper-troposphere ambient air temperature \( T_{Ob} \) and found to be equivalent when compared with ADC air temperature calculations (Goodrich Sensor Systems 2002a):

$$ T_{Ob} = T_G - 10^\circ\text{C}. \tag{1} $$

Aircraft geographical position and altitude were plotted on printed MM5 and WRF forecast maps and corresponding MM5 or WRF upper-troposphere temperature values were manually recorded into data logs.

c. Temperature observation and aircraft instrument system verification

Upper-troposphere radiosonde temperature \( T_R \) records were retrieved postflight near the actual aircraft flight tracks when available using the University of Wyoming Upper Air Sounding Database (University of Wyoming 2012) and are shown in Table 1. Aircraft temperature observation altitudes are not shown on radiosonde data, requiring interpolation of \( T_R \) rounded to the whole number corresponding to aircraft navigation system display temperature format. Here \( T_R \) was corrected for atmospheric heating or cooling as a result of time \( T_{RC} \) through interpolation of \( T_R \) between the 0000 and 1200 UTC soundings surrounding the time of aircraft passage near the sounding station. The term \( T_{Ob} \) is compared with \( T_{RC} \) by

$$ T_\Delta = T_{RC} - T_{Ob}, \tag{2} $$
yielding a temperature delta \( T_\Delta \) range from \(+2^\circ\text{C} \) (12 February) to \(-3^\circ\text{C} \) (4 April). The \( T_\Delta \) remained warmer during most flights in February 2009 while decreasing to a cooling trend for flights in April 2009 over varying lateral distance deviations between sounding locations and \( T_{Ob} \) at aircraft observation heights. Although interpolation can introduce some uncertainty into the analysis, averaged \( T_\Delta \) of the seven sounding stations within 100 km of the aircraft indicated small delta values (Table 1). Here \( T_\Delta \) indicated an average value of \(-1.0^\circ\text{C} \) (standard deviation of 1.2°C), suggesting no visible shift in \( T_\Delta \) measurements, which may be due to indicator malfunction or probe inlet blockage. Therefore, comparison of aircraft observations with radiosonde measurements promoted reasonable confidence in data purity similar to Moninger et al. (2003) and Benjamin et al. (2010).

d. Source of modeling data

Determining temperature error and vertical velocity coupling for MM5 and WRF within the upper troposphere required employment of model forecasts in a similar manner as a potential user (i.e., aviation flight planning). To simulate forecast user employment, access was obtained to use the AFWA Joint Air Force and Army Weather Information Network (JAAWIN) Interactive Grid Analysis and Display System (IGrADS).
to run MM5 and WRF forecasts in which \( T_{Ob} \) were
compared (Telfeyan et al. 2005). At the time of study
initiation, JAAWIN’s authorized computer model cov-
erage was the MM5 for North America and version
3.0.1.1 of the WRF variational data assimilation (WRF-
Var) for the Atlantic Ocean, Europe, and southwest
Asia. The IGrADS interface allowed forecast users to
select certain forecast physical parameters such as
isotherms, lower and upper height boundaries, model
route start and stop locations, a model route segment
midpoint, and forecast start and stop times for the
model route segments. MM5 and WRF physics pack-
gages and domain settings were configuration controlled
by JAAWIN with no ability for modification by the
IGrADS user serving as a limitation preventing physics
package modification for testing.

JAAWIN’s forecast domains covered the landmasses
of North America (MM5), Europe, and Asia (WRF).
JAAWIN-controlled parent domains for MM5 and
WRF were set at 45 km with 15-km nesting encom-
passing all modeled flight tracks. MM5 and WRF
utilized the Rapid Radiative Transfer Model (RRTM)
longwave radiation and simple shortwave radiation
schemes with the Noah land surface model. The Medium-
Range Forecast planetary boundary layer and Kain–
Fritsch cumulus parameterization schemes were selected
by JAAWIN for MM5 using fixed-sigma vertical layer-
ing and Multivariate Optimum Interpolation assim-
ilation. MM5 utilized the upper-radiative-boundary
conditions that were standard on the MM5 model,
while JAAWIN employed vertical velocity and tradi-
tional Rayleigh dampening for WRF upper-boundary
conditions. JAAWIN’s approved WRF physics pack-
gages consisted of the Yonsei University planetary
boundary layer, new Kain–Fritsch cumulus parameter-
ization, and WRF Single Moment Five (WSM 5)
schemes employing floating sigma vertical layering
and three-dimensional variational data assimilation
(3DVAR). The vertical boundaries of the MM5 and WRF
model runs were set to begin at the surface and terminate
at a height of 9100 m. In between 500 and 400 hPa the
models have five layers, each of them between 500 and
540 m thick.

Upper-troposphere temperature observation time
periods were identified during February and April 2009
based on aircraft availability of flights over sparsely
traveled or radiosonde deficient regions within the up-
per troposphere. Once flight routes were designated and
flight planning completed, the MM5 and WRF multileg
forecast route parameters were entered into JAAWIN’s
online IGrADS user interface 3 h prior to flight de-
parture and completed within 5 min of model route

<table>
<thead>
<tr>
<th>Sortie date (2009)</th>
<th>Station time (UTC)</th>
<th>Aircraft obs time (UTC)</th>
<th>Station</th>
<th>Distance* (km)</th>
<th>Height (m)</th>
<th>( T_R )</th>
<th>( T_{RC} )</th>
<th>( T_{Ob} )</th>
<th>( T_\Delta )</th>
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<td>1910</td>
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<td>–29</td>
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<td>De Bilt, Netherlands</td>
<td>107</td>
<td>7013</td>
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<td>Meiningen, Germany</td>
<td>96</td>
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<tr>
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<td>0505</td>
<td>Erzurum, Turkey</td>
<td>85</td>
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<td>–40</td>
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<td>0800</td>
<td>Erzurum</td>
<td>93</td>
<td>6098</td>
<td>–21**</td>
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<td>142</td>
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<td>–23</td>
<td>–23</td>
<td>–26</td>
<td>–3</td>
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</table>

* Lateral distance delta of the radiosonde geographic position from aircraft geographic position at aircraft observation altitude without
regard to time of observations. Accuracy is ±20 km (Seidel et al. 2011).
** Samsun 0000 UTC sounding used in place of Erzurum 0000 UTC sounding because of unavailable data.
parameter entry. Although temperature observation flight routes used great circle courses, JAAWIN’s IGrADS user interface system operated in straight line courses requiring desired flight altitudes, initial starting point, midpoint, and termination point. The takeoff time at the start point, estimated time over the midpoint, and estimated landing time at the termination point were entered into the IGrADS user interface producing time accurate forecasts across the flight route requiring no additional time correction needed between aircraft observed and forecast temperature data. MM5 and WRF forecast outputs were printed for $T_{Ob}$ comparison with isotherms depicted in degrees Celsius, forecast vertical velocity depicted in microbars per second (1 $\mu$bar = 0.1 Pa), cloud formation profiles, altitude in thousands of feet, and latitude and longitude in degrees (Fig. 4).

During flight, forecast (denoted by subscript $F$) upper-troposphere temperature $T_{F}$ and vertical velocity $V_{VF}$ were extracted from the MM5 and WRF printed outputs. A grid was included on each printed MM5 and WRF output and used to plot aircraft position (latitude and longitude) on the $x$ axis and aircraft altitude in thousands of feet on the $y$ axis. Isotherms on the MM5 and WRF forecast outputs were in 4$^\circ$ increments and isotherms were not always depicted at the intersection of aircraft position and altitude so $T_{F}$ was interpolated by

$$T_{F} = \frac{(A_{Ob} - A_{L})(T_{U} - T_{L})}{A_{U} - A_{L}} + T_{L}, \quad (3a)$$

where $A_{Ob}$ is the aircraft observation altitude, $A_{L}$ is the matching isotherm altitude height below $A_{Ob}$, $A_{U}$ is the matching isotherm altitude height above $A_{Ob}$, $T_{L}$ is the modeled isotherm corresponding to $A_{L}$, and $T_{U}$ is the modeled isotherm corresponding to $A_{U}$ resulting in a computed $T_{F}$ rounded to the whole number corresponding to aircraft navigation system temperature format. The $V_{VF}$ microbar gradients varied on the MM5 and WRF forecast outputs and microbars were not always depicted at the aircraft position and altitude intersection, therefore interpolation was accomplished by

$$V_{VF} = \frac{(LL_{Ob} - LL_{L})(V_{VR} - V_{VL})}{LL_{R} - LL_{L}} + V_{VL}, \quad (3b)$$

where $LL_{Ob}$ represents the latitude and longitude of the observation, $LL_{L}$ is the latitude and longitude of the model depicted microbar intercept left of $LL_{Ob}$ on the $x$ axis, $LL_{R}$ is the model depicted microbar intercept on the $x$ axis to the right of $LL_{Ob}$, $V_{VR}$ is the corresponding microbar value of $LL_{L}$, and $V_{VL}$ is the corresponding microbar value of $LL_{R}$. Differences between the latitude and longitude points ($LL_{Ob}$, $LL_{L}$, and $LL_{R}$) in Eq. (3b) represent distances in kilometers and were computed using global positioning system (GPS) software. Manual extraction of model values occurred three times with navigational plotting equipment capable of measuring in 1.0$^\circ$ angles and dividing spatial areas down to 1.5 cm. Interpolation presents a potential error for the analysis and was mitigated to the maximum extent possible by using the average of the three interpolated values suggesting the estimated error to be less than 0.5$^\circ$C and 0.5 $\mu$bar s$^{-1}$ based on the resolution of the model values.

e. Postflight processing

With lateral distance deviation from MM5 and WRF modeled tracks noted as insignificant ($R = 0.1$) and $T_{G}$ and $T_{F}$ computational resolutions of 1.0$^\circ$C, lateral corrections of $T_{Ob}$ to match MM5 and WRF modeled flight tracks were deemed unnecessary. Here $T_{Ob}$ were arranged by smallest to largest lateral distance deviation from the modeled flight tracks, and $T_{Ob}$ within 100 km of lateral deviation were used to provide representative data nearest the modeled flight tracks for analysis. Data was classified into 0–50- and 51–100-km datasets to determine a point where temperature error and $VV_{F}$ coupling may no longer exist. Surface elevation above sea level was derived through charted GPS elevation data and classified into sets of 100-m increments ascending in height from 0 to 699 m above sea level. For heights >699 m in surface elevation above sea level, data points were combined into varying categories because of diminishing $T_{Ob}$ data populations $n$.

Upper-troposphere temperature observations were classified referencing the Harmonized World Soil Database (HWSD) depicted in Fig. 5 to determine if upper-troposphere temperature error and $VV_{F}$ coupling favored a surface type (Fischer et al. 2011). The HWSD map is a compilation of six separate supplementary databases allowing surface type classification by land, water, grass/scrub brush, crops, forest, no vegetation, and urban development. The database map allowed category definition up to $>75\%$ vegetation type; however, interference by blending of the 50$\%$–75$\%$ and $>75\%$ map categories caused difficulty declaring $>75\%$ coverage for all $T_{Ob}$. Therefore the surface type was declared using $>50\%$ for vegetation cover type and $>10\%$ urban coverage. Snow cover was indicated by archived data over forest surface type on both MM5 flights over southeast Canada (from Quebec to Caribou; $n = 7$) and on both WRF flights between Regensburg, Germany, and the Czech Republic border ($n = 4$). All other surface types did not indicate snow cover (Montreal Weather Center 2012; National Weather Service 2012).
f. Analysis

RMSE was determined for each dataset measuring skill as a potential marker to highlight the presence of temperature error and \( VV_F \) coupling. The initial step was to determine the upper-troposphere temperature error \( TE \) between \( T_{Ob} \) and \( T_F \) defined as

\[
T_E = T_{Ob} - T_F.
\]  

(4a)

RMSE was then computed for \( T_E \) datasets by

\[
RMSE = \left[ \frac{1}{n} \sum_{j=1}^{n} (T_{Ej})^2 \right]^{1/2},
\]  

(4b)

where \( n \) represents the number of observations (Stull 2000). A regression analysis was performed on each dataset to establish a coupling relationship between \( T_E \) and \( VV_F \) using a simple linear model detailed by Riggs (1985) and defined as

\[
T_E = a(VV_F) + b,
\]  

(5a)

where the slope \( a \) of the linear equation is computed by

\[
a = \frac{n \sum_{j=1}^{n} (VV_{Fj} T_{Ej}) \sum_{j=1}^{n} VV_{Fj} \sum_{j=1}^{n} T_{Ej}}{n \sum_{j=1}^{n} VV_{Fj}^2 - \left( \sum_{j=1}^{n} VV_{Fj} \right)^2},
\]  

(5b)

and the intercept \( b \) of the linear equation derived from

\[
b = \frac{\sum_{j=1}^{n} T_{Ej} - a \sum_{j=1}^{n} VV_{Fj}}{n}.
\]  

(5c)

The coefficient of determination \( R^2 \) was used as a primary discriminator to assess the performance of the linear data fit calculated by

FIG. 4. WRF upper-troposphere vertical cross-sectional forecast on 14 Feb 2009 for the planned route of flight between England and Romania. Model grid spacing is defaulted to 45 km. Shown are temperature (°C; dotted horizontal contour lines), wind direction (barbs, north at top of page), wind velocity [kt (1 kt \( \sim \) 0.5 m s\(^{-1}\)); barb flags], cloud prediction (dark solid line), and vertical velocity (mbar s\(^{-1}\); vertical dotted lines). Forecast initiation was for England (label a), with termination in Romania (label c) and midpoint in the Czech Republic (label b), as depicted by the map inset at top right. Latitude (°N) and longitude (°W/E) are displayed at bottom. Altitude is displayed on the left scale [mb (= hPa)], and pressure altitude is shown on the right scale in flight levels (FL) equating to thousands of feet (160 = 16 000 ft; 1 ft \( \sim \) 0.3048 m).
R² = \frac{SS_R}{SS_T}, \quad (6a)

with SS_R representing the sum squares of deviation of \( T_E \) from the experimental average error \( T_{E_{avg}} \) for each observation point \( j \) (1 ≤ \( j \) ≤ \( n \)):

\[ SS_R = \sum_{j=1}^{n} (T_{E_j} - T_{E_{avg}})^2 , \quad (6b) \]

and SS_T signified by the totals of sum square error and regression error depicted as

\[ SS_T = SS_E + SS_R \quad (6c) \]

in which SS_E represents the sum square error of the \( T_E \) residuals \( \gamma \) of \( j \) (Riggs 1985):

\[ SS_E = \sum_{j=1}^{n} (r_j - r_{avg})^2 , \quad (6d) \]

A standard error of regression \( SE_R \) was computed to further substantiate fit of regression through assessment of dataset accuracy (Riggs 1985). Here \( SE_R \) depicted the experimental accuracy related to \( T_E \) along the regression line, expressed as

\[ SE_R = \left( \frac{SS_R}{n-2} \right)^{1/2} , \quad (7) \]

The lower (denoted by subscript \( L \)) \( VV_{FL} \) and upper (denoted by subscript \( U \)) \( VV_{FU} \) bounded confidence interval (CI) of 0.95 was computed regarding \( VV_F \) using

\[ (CI = 0.95) = VV_{F_j} - SE \times t_{1-p_j}. \quad (8a) \]

In this definition \( t \) is the number resultant from the \( t \) statistic, and the \( p \) value \( P \) from the statistical significance test of \( VV_F \) and \( SE \) the standard error of \( VV_F \):

\[ SE = \left\{ \frac{SS_E \left[ \frac{1}{n-(i+1)} \right]}{\sum_{j=1}^{n} VV_{F_j}^2} \right\}^{1/2} , \quad (8b) \]

where \( i \) is the number of independent variables (Riggs 1985).

The \( T_F \) and \( VV_F \) coupling identification was accomplished using \( R^2 \geq 0.1 \), rounded to one decimal place where \( R^2 = 1.0 \) demonstrates a perfect fit (Knutti et al. 2010). After \( R^2 \) was determined, CI was tested by

\[ VV_{FL}(CI = 0.95) < 0 > VV_{FU}(CI = 0.95), \quad (9) \]

where inclusion of zero (CI = 0) signifies rejection of \( T_E \) and \( VV_F \) coupling qualifying determinations made by \( R^2 = 0.0 \).
3. Results

a. MM5 and WRF upper-troposphere forecast temperature RMSE evaluation

RMSE scores were computed for all upper-troposphere MM5 and WRF $T_E$ data subcategories listed in Tables 2–6 and tested as markers to help identify $T_E$ and VV$_F$ coupling prior to regression analysis. RMSE analysis indicated WRF exhibited good ($T_E$ RMSE $\leq 2.0^\circ$C) $T_E$ skill (WRF 0–50-km land $T_E$ RMSE $= 1.8^\circ$C; WRF 51–100-km land $T_E$ RMSE $= 1.1^\circ$C) while MM5 displayed moderate ($2.1^\circ \leq T_E$ RMSE $\leq 5.0^\circ$C) $T_E$ skill (MM5 0–50-km land $T_E$ RMSE $= 2.2^\circ$C; and MM5 51–100-km land $T_E$ RMSE $= 2.4^\circ$C) in upper-troposphere forecasts over land between 0–50- and 51–100-km lateral distance deviation from modeled flight tracks (MM5 showed moderate skill over grass/scrub brush between 100 and 199 m above sea level (MM5 51–100-km water $T_E$ RMSE $= 1.5^\circ$C) and WRF ($T_E$ RMSE $= 1.0^\circ$C) upper-troposphere forecasts over water between 51- and 100-km lateral distance deviation from modeled flight tracks.

MM5 indicated good $T_E$ skill in upper-troposphere forecasts over surface elevations $\leq 299$ m above sea level differing by a $T_E$ RMSE $= 0.2^\circ$C (Table 3). MM5 exhibited moderate $T_E$ skill over surface elevations between 300 and 399 m (MM5 300–399-m $T_E$ RMSE $= 3.4^\circ$C) and between 400 and 499 m above sea level (MM5 400–499-m $T_E$ RMSE $= 3.7^\circ$C) (Table 3). WRF indicated moderate $T_E$ skill over surface elevations between 100 and 199 m above sea level (WRF 100–199-m $T_E$ RMSE $= 2.8^\circ$C) improving in $T_E$ skill between 0 and 99 m (WRF 0–99-m $T_E$ RMSE $= 1.3^\circ$C), 200 and 299 m (WRF 200–299-m $T_E$ RMSE $= 0.8^\circ$C), 300 and 399 m (WRF 300–399-m $T_E$ RMSE $= 1.2^\circ$C), and between 400 and 499 m (WRF 400–499-m $T_E$ RMSE $= 1.5^\circ$C) surface elevation above sea level. MM5 was not utilized over surface elevations $> 499$ m above sea level (Europe and southwest Asia) but WRF was used for upper-troposphere forecasts producing $T_E$ RMSE scores ranging between 0.7$^\circ$C (good) and 2.9$^\circ$C (moderate) over surface elevations $> 499$ m above sea level indicating varied $T_E$ skill with increased surface elevation (Table 4).

MM5 and WRF upper-troposphere forecast exhibited moderate $T_E$ skill over grass/scrub brush (MM5 grass/scrub brush $T_E$ RMSE $= 2.3^\circ$C; WRF grass/scrub brush $T_E$ RMSE $= 2.4^\circ$C). WRF forecasts indicated good $T_E$ skill over crops (WRF crops $T_E$ RMSE $= 0.9^\circ$C), while MM5 forecast $T_E$ skill remained moderate (MM5 crops $T_E$ RMSE $= 4.1^\circ$C) (Table 5). MM5 and WRF upper-troposphere forecasts exhibited good $T_E$ skill over forest regions (MM5 forest $T_E$ RMSE $= 0.8^\circ$C; WRF forest $T_E$ RMSE $= 1.8^\circ$C) and urban areas (MM5 urban $T_E$ RMSE $= 0.9^\circ$C; WRF urban $T_E$ RMSE $= 1.5^\circ$C) (Table 6). MM5 showed moderate $T_E$ skill over nonurban areas (MM5 nonurban $T_E$ RMSE $= 2.4^\circ$C and nonvegetated areas were not used in MM5 so a $T_E$ RMSE score was not computed. WRF was utilized over non-vegetated areas indicating good $T_E$ skill (WRF no vegetation $T_E$ RMSE $= 1.6^\circ$C) similar to upper-troposphere forecasts over areas of nonurban development (WRF nonurban $T_E$ RMSE $= 1.3^\circ$C).

Table 2. RMSE ($^\circ$C) and regression analysis results for temperature error $T_E$ ($^\circ$C) and forecast vertical velocity ($\mu$m s$^{-1}$) VV$_F$ coupling for lateral distance deviation from MM5 and WRF modeled flight track over land and water. Boldface figures indicate $R^2 \geq 0.1$; CI $\neq 0$, and italicized figures indicate CI $= 0$.

<table>
<thead>
<tr>
<th></th>
<th>0–50 km</th>
<th>51–100 km</th>
</tr>
</thead>
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</tr>
<tr>
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</tr>
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</tr>
<tr>
<td>WRF</td>
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<td>2.0</td>
</tr>
<tr>
<td>$R^2$</td>
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<td></td>
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</tr>
<tr>
<td>WRF</td>
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<td>0.0</td>
</tr>
<tr>
<td>SE$_R$</td>
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<td></td>
</tr>
<tr>
<td>MM5</td>
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</tr>
<tr>
<td>WRF</td>
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<td>1.9</td>
</tr>
<tr>
<td>$a$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MM5</td>
<td>0.5</td>
<td>0.0</td>
</tr>
<tr>
<td>WRF</td>
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<td>0.0</td>
</tr>
<tr>
<td>$b$</td>
<td></td>
<td></td>
</tr>
<tr>
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<tr>
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<tr>
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<td></td>
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<td>VV$_{FU}$ (CI = 0.95)</td>
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<td></td>
</tr>
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<td>-8.2</td>
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<tr>
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<td>-1.4</td>
</tr>
<tr>
<td>VV$_{FL}$ (CI = 0.95)</td>
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<td></td>
</tr>
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<td>MM5</td>
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<td>4.2</td>
</tr>
<tr>
<td>WRF</td>
<td>0.3</td>
<td>0.2</td>
</tr>
</tbody>
</table>

b. Lateral distance deviation from MM5 and WRF modeled flight track

MM5 and WRF upper-troposphere $T_E$ data within 100 km laterally of MM5 and WRF forecast modeled flight tracks were tested and results detailed in Table 2. Strong $T_E$ and VV$_F$ coupling ($R^2 = 0.6$–0.9) was indicated in MM5 upper-troposphere forecasts over land between 0–50- and 51–100-km lateral distance deviation from modeled flight tracks where MM5 0–50-km land and MM5 51–100-km land $R^2 = 0.6$ and confidence intervals were exclusive of zero (CI $\neq 0$). The $T_E$ and VV$_F$ coupling was rejected between 0–50- and 51–100-km lateral distance deviation from modeled flight tracks in MM5 upper-troposphere forecasts over water where MM5 0–50-km and MM5 51–100-km water ($R^2 = 0.0$). WRF upper-troposphere forecasts exhibited moderate $T_E$ and VV$_F$ coupling ($R^2 = 0.3$–0.5) over land between...
0- and 50-km lateral distance deviation from modeled flight tracks where WRF 0–50-km land $R^2 = 0.3$ (CI ≠ 0) and no $T_E$ and $V_V^F$ coupling exhibited over water between 0- and 50-km lateral distance deviation from modeled flight tracks. Between 51- and 100-km lateral distance deviation from modeled flight tracks, WRF upper-troposphere forecasts continued to indicate moderate $T_E$ and $V_V^F$ coupling over land (WRF 51–100-km land $R^2 = 0.3$; CI ≠ 0) with no indication of $T_E$ and $V_V^F$ coupling in WRF upper-troposphere forecasts over water (WRF 51–100-km water $R^2 = 0.0$).

c. Changes in surface elevation above sea level

MM5 and WRF $T_E$ surface elevation datasets were tested determining if $T_E$ and $V_V^F$ coupling in MM5 and WRF upper-troposphere forecasts is specific to surface elevation above sea level. Strong to moderate $T_E$ and $V_V^F$ coupling was exhibited by MM5 (MM5 300–399 m $R^2 = 0.8$) and WRF (WRF 300–399 m $R^2 = 0.4$) upper-troposphere forecasts over surface elevations between 300 and 399 m above sea level exhibited by MM5 and WRF 300–399-m CI ≠ 0 (Table 3). No indication of $T_E$ and $V_V^F$ coupling was indicated in MM5 upper-troposphere forecasts over surface elevations between 0 and 99 m above sea level where MM5 0–99-m $R^2 = 0.0$. MM5 and WRF upper-troposphere forecasts over surface elevations between 100–299 and 400–499 m above sea level indicated no $T_E$ and $V_V^F$ coupling and MM5 and WRF 100–299-m and 400–499-m CI = 0. Surface elevation datasets >499 m above sea level contained no MM5 upper-troposphere $T_E$ data; however, WRF

<table>
<thead>
<tr>
<th>RMSE</th>
<th>MM5</th>
<th>0–99 m</th>
<th>100–199 m</th>
<th>200–299 m</th>
<th>300–399 m</th>
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<tr>
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<td>1.5</td>
<td></td>
</tr>
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<td>$R^2$</td>
<td>MM5</td>
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<td>0.1</td>
<td>0.8</td>
<td>0.0</td>
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<tr>
<td>WRF</td>
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</tr>
<tr>
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<td>MM5</td>
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<td>1.4</td>
<td>1.5</td>
<td>0.7</td>
</tr>
<tr>
<td>WRF</td>
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<td>0.8</td>
<td>1.0</td>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td>$a$</td>
<td>MM5</td>
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<td>0.2</td>
<td>0.8</td>
<td>1.3</td>
<td>0.0</td>
</tr>
<tr>
<td>WRF</td>
<td>0.4</td>
<td>0.8</td>
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<td>0.2</td>
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</tr>
<tr>
<td>$b$</td>
<td>MM5</td>
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<td>0.2</td>
<td>−0.9</td>
<td>−1.6</td>
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</tr>
<tr>
<td>WRF</td>
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<td>−1.5</td>
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<td>−0.7</td>
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</tr>
<tr>
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<td>3</td>
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<td>WRF</td>
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<td>13</td>
<td>11</td>
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</tr>
<tr>
<td>$V_V^F$ (CI = 0.95)</td>
<td>MM5</td>
<td>−0.4</td>
<td>−0.3</td>
<td>−1.5</td>
<td>0.9</td>
<td>−5.1</td>
</tr>
<tr>
<td>WRF</td>
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<td>−3.2</td>
<td>−0.7</td>
<td>0.1</td>
<td>−1.8</td>
<td></td>
</tr>
</tbody>
</table>

| Table 4. As in Table 3, but for surface elevations >499 m above sea level. |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
|                | 500–599 m       | 600–699 m       | 700–999 m       | 1000–1299 m     | >1300 m         |
| RMSE           | MM5             | WRF             | MM5             | WRF             | MM5             |
| MM5            | ---             | ---             | ---             | ---             | ---             |
| WRF            | 1.1             | 1.2             | 2.9             | ---             | 0.7             |
| $R^2$          | MM5             | ---             | ---             | ---             | ---             |
| WRF            | 0.6             | **0.9**         | **1.0**         | ---             | 0.4             |
| $SE_R$         | MM5             | ---             | ---             | ---             | ---             |
| WRF            | 0.3             | 0.9             | 0.9             | ---             | 0.2             |
| $a$            | MM5             | ---             | ---             | ---             | ---             |
| WRF            | 0.3             | 0.8             | 0.9             | ---             | 0.3             |
| $b$            | MM5             | ---             | ---             | ---             | ---             |
| WRF            | −0.2            | −0.7            | −0.2            | ---             | 0.4             |
| $n$            | MM5             | ---             | ---             | ---             | ---             |
| WRF            | 6               | 5               | 8               | ---             | 11               |
| $V_V^F$ (CI = 0.95) | MM5 | --- | --- | --- | --- |
| WRF | −0.7 | **0.5** | **0.8** | --- | −0.1 |
| $V_V^F$ (CI = 0.95) | MM5 | --- | --- | --- | --- |
| WRF | 2.1 | **2.1** | **0.4** | --- | 0.3 |
upper-troposphere forecasts exhibited strong $T_E$ and VVF coupling over surface elevations between 600 and 699 m (WRF 600–699-m $R^2 = 0.9$; CI $\neq$ 0) and between 700 and 999 m (WRF 700–999 m $R^2 = 1.0$; CI $\neq$ 0) above sea level with $n \geq 8$ (Table 4).

d. Surface type

Upper-troposphere temperature error data were classified by surface type isolating $T_E$ and VVF coupling in MM5 and WRF over land, water, vegetation, and urban surface type with findings displayed in Tables 5 and 6. Weak $T_E$ and VVF coupling ($R^2 = 0.1$ or 0.2) was indicated in MM5 (MM5 land $R^2 = 0.5$; CI $\neq$ 0) and WRF (WRF land $R^2 = 0.2$; CI $\neq$ 0) upper-troposphere forecasts over land, while $T_E$ and VVF coupling was not present in MM5 and WRF upper-troposphere forecasts over water with MM5 and WRF water CI $= 0$. In MM5 upper-troposphere forecasts over grass/scrub brush, $T_E$ and VVF coupling was not indicated; however, WRF upper-troposphere forecasts did indicate moderate $T_E$ and VVF coupling over grass/scrub brush (WRF grass/scrub brush $R^2 = 0.4$; CI $\neq$ 0) and weak to moderate $T_E$ and VVF coupling was indicated in MM5 (MM5 crops $R^2 = 0.2$; CI $\neq$ 0) and WRF (WRF crops $R^2 = 0.3$; CI $\neq$ 0) upper-troposphere forecasts over crops (Table 5). In MM5 and WRF upper-troposphere forecasts over forest-covered surfaces with CI $= 0$, $T_E$ and VVF coupling was not detected and there was no indication of $T_E$ and VVF coupling in WRF upper-troposphere forecasts over nonvegetated areas (WRF no vegetation $R^2 = 0.0$). MM5 and WRF upper-troposphere forecasts indicated $T_E$ and VVF coupling differently over urban influences, where MM5 upper-troposphere forecasts (MM5 nonurban $R^2 = 0.4$; CI $\neq$ 0) indicated $T_E$ and VVF coupling over nonurban influences and WRF upper-troposphere forecasts (WRF urban $R^2 = 0.3$; CI $\neq$ 0) indicated $T_E$ and VVF coupling over urban influences (Table 6).

| Table 5. RMSE ($^\circ$C) and regression analysis results for upper-troposphere temperature error $T_E$ ($^\circ$C) and forecast vertical velocity (mbar s$^{-1}$) VVF coupling over land, water, crops, and grass/scrub brush surface types. Boldface figures indicate $R^2 \geq 0.1$; CI $\neq$ 0, and italicized figures indicate CI $= 0$. |
|---|---|---|---|
| | Land | Water | Grass/scrub brush |
| RMSE | MM5 | 2.3 | 1.7 | 2.3 | 4.1 |
| | WRF | 1.5 | 1.8 | 2.4 | 0.9 |
| $R^2$ | MM5 | 0.5 | 0.1 | 0.0 | 0.2 |
| | WRF | 0.2 | 0.0 | 0.4 | 0.3 |
| SE$_R$ | MM5 | 0.5 | 0.8 | 0.7 | 0.3 |
| | WRF | 1.3 | 1.6 | 1.8 | 0.6 |
| $a$ | MM5 | 0.7 | 0.7 | $-0.3$ | 0.3 |
| | WRF | 0.2 | 0.0 | 0.3 | 0.5 |
| $b$ | MM5 | $-0.9$ | $-1.1$ | $-2.9$ | $-4.7$ |
| | WRF | $-0.6$ | $-0.7$ | $-1.3$ | $-0.4$ |
| $n$ | MM5 | 59 | 11 | 10 | 8 |
| | WRF | 104 | 53 | 26 | 49 |
| VVF$_{FU}$ (CI = 0.95) | MM5 | 0.5 | $-0.1$ | $-1.3$ | $-3.6$ |
| | WRF | 0.2 | $-0.2$ | 0.1 | 0.3 |
| VVF$_{FL}$ (CI = 0.95) | MM5 | 0.9 | 0.4 | 0.8 | 5.6 |
| | WRF | 0.3 | $-0.4$ | 0.4 | 0.7 |

| Table 6. As in Table 5, but for forest, no vegetation, urban, and nonurban surface types. |
|---|---|---|---|
| | Forest | No vegetation | Urban | Nonurban |
| RMSE | MM5 | 1.8 | — | 0.9 | 2.4 |
| | WRF | 0.8 | 1.6 | 1.5 | 1.3 |
| $R^2$ | MM5 | 0.1 | — | 0.3 | 0.4 |
| | WRF | 0.1 | 0.0 | 0.3 | 0.1 |
| SE$_R$ | MM5 | 1.4 | — | 0.5 | 1.6 |
| | WRF | 0.8 | 1.6 | 0.3 | 1.3 |
| $a$ | MM5 | 0.3 | — | 0.3 | 0.7 |
| | WRF | 0.3 | 0.2 | 0.2 | 0.3 |
| $b$ | MM5 | 0.3 | — | 0.5 | $-1.0$ |
| | WRF | 0.1 | $-0.9$ | $-0.3$ | $-0.1$ |
| $n$ | MM5 | 41 | — | 4 | 55 |
| | WRF | 11 | 18 | 69 | 35 |
| VVF$_{FU}$ (CI = 0.95) | MM5 | 0.0 | — | $-0.8$ | $-1.1$ |
| | WRF | $-0.3$ | $-0.4$ | $-0.6$ | 0.4 |
| VVF$_{FL}$ (CI = 0.95) | MM5 | 0.6 | — | 1.3 | $-2.1$ |
| | WRF | 0.8 | 0.8 | $-1.2$ | $-0.6$ |

4. Discussion

Regression analysis indicated significant statistical evidence supporting $T_E$ and VVF coupling in MM5 and WRF upper-troposphere forecasts within 100-km lateral distance deviation from modeled flight tracks, over different surface type and surface elevations above sea level. An attempt was made to correlate RMSE with $T_E$ and VVF coupling that posted an $R = 0.0$ indicating RMSE is not a good indicator of $T_E$ and VVF coupling presence in MM5 and WRF upper-troposphere forecasts. Rejection of RMSE as a $T_E$ and VVF coupling indicator in MM5 and WRF upper-troposphere forecasts is a result of similar RMSE values where $T_E$ and VVF coupling exists (i.e., WRF land RMSE = 1.5°C and $R^2 = 0.2$) and where $T_E$ and VVF coupling is not present (i.e., WRF water RMSE = 1.8°C and $R^2 = 0.0$) (Table 5). Examination of Fig. 3 indicated positive and negative temperature biases that tend to mirror VVF and initially pointed toward $T_E$ and VVF coupling in MM5 and WRF upper-troposphere forecasts. When $T_{Ob}$ were arranged in the order of coldest to warmest a visual depiction of $T_E$ and VVF coupling was displayed corresponding to noticeable fluctuations in $T_E$ (Fig. 6).

Figure 6 displays WRF $T_E$ and $T_{Ob}$ data over land illustrating $T_E$ and VVF coupling where $T_{Ob}$ were arranged from coldest to warmest and is characteristic of MM5 and WRF upper-troposphere forecasts where $T_E$
and VV_F coupling is present ($R^2 \geq 0.1; CI \neq 0$). Figure 6
suggests when $T_E \geq 2.0^\circ C$ a corresponding increase in
VV_F magnitude is observed as exhibited by $n = 25$, $n = 65$, and $n = 81$.

Figure 7 displays WRF $T_F$ and $T_{Ob}$ data over water
where $T_{Ob}$ were arranged from coldest to warmest and
no $T_E$ and VV_F coupling present ($R^2 = 0.0$ or CI = 0),
which is representative for MM5 and WRF upper-
troposphere forecasts that did not indicate $T_E$ and VV_F
coupling ($R^2 = 0.0$ or CI = 0). The increases in magnitude
of VV_F displayed in Fig. 6 corresponding to $T_E \geq
2.0^\circ C$ were not displayed in Fig. 7 where changes in VV_F
magnitude were independent of $T_E$ in MM5 and WRF
upper-troposphere forecasts over water ($n = 10$, $n = 36$,
and $n = 44$). Therefore $T_E$ appears to be the driver in
erroneous VV_F events over land in MM5 and WRF
upper-troposphere forecasts, which may result in erro-
aneous cloud formation prediction causing incorrect
forecasting of precipitation and turbulence.

Since $T_E$ and VV_F coupling in MM5 (MM5 land
$R^2 = 0.5; CI \neq 0$) and WRF (WRF land $R^2 = 0.2$;
CI $\neq 0$) upper-troposphere forecasts occurs over land
rather than over water (WRF and MM5 water $R^2 = 0.0$
or CI = 0) the possibility exists that differential heating
and/or humidity may be a cause for MM5 and WRF
upper-troposphere $T_E$ (Table 5). Where MM5 and WRF
upper-troposphere forecasts have a cold bias, entrain-
ment of air into areas of VV_F may actually be dryer and
warmer than predicted, causing increased $T_E$ and over-
predicting VV_F, which creates incorrect turbulence intensity
(Fig. 6; $n = 29$, $n = 69$, and $n = 97$). Underforecasting of
temperature in MM5 and WRF upper-troposphere
forecasts may be tied to upwelling longwave radiation
incorrectly parameterized over land in RRTM because of
changes in upwelling longwave radiation angle and azi-
muth resulting from changes in slope at different surface
elevations above sea level (Yang et al. 2012). MM5 and
WRF upper-troposphere $T_E$ may possibly be forcing
incorrect VV_F through changes in radiative flux as a result
of land surface changes between urban and urban-free
regions analogous to large cities surrounded by expanse
of rolling hills and vegetation. The $T_E$ and VV_F coupling
is not observed in MM5 and WRF upper-troposphere
forecasts over water where water bodies do not experi-
ence land surface changes allowing for homogeneous
radiative flux and decreases in occurrence of $T_E$ as de-
picted in Fig. 7.

A second mechanism for MM5 and WRF upper-
troposphere $T_E$ instigating incorrect VV_F may be en-
trainment of more water vapor than predicted in areas of
VV_F, which releases latent heat and warms the area
surrounding VV_F, creating a larger $T_E$ and propagating
an incorrect increase in VV_F. One possible cause for
increased humidity is the disturbance of water runoff
patterns causing soil to remain saturated and creating
a source for increased humidity not captured in MM5
and WRF calculations. Evapotranspiration rates from
croplands and urban vegetation irrigation may be
greater than estimated over grass/scrub brush and non-
urban regions releasing more moisture than predicted
increasing humidity that is unaccounted for in MM5 and
WRF. Snow cover was observed over a small subset of
forest surface type (MM5 $n = 7$; WRF $n = 4$) but was not
considered a factor since $T_E$ and VV_F coupling was not
exhibited in general over forest surface type (Table 6).
Incorrect evapotranspiration rates could be a result of

![Fig. 6. Upper-troposphere aircraft temperature observations $T_{Ob}$ and WRF temperature forecasts $T_F$ over land compared with temperature error $T_E$ and forecast vertical velocity VV_F coupling ($R^2 = 0.2$).](image)
deforestation and replacement with broadleaf vegetation such as aspen, corn, or grasses, which have higher evapotranspiration rates than traditional forest vegetation such as pine and/or leaf loss because of seasonal changes. This may explain why $T_E$ and $VV_F$ coupling is observed in MM5 and WRF upper-troposphere forecasts over crop and grass/scrub brush regions while $T_E$ and $VV_F$ coupling is not exhibited in MM5 and WRF upper-troposphere forecasts over forested areas.

Addressing the corrective factors within the physics packages used by AFWA for JAAWIN applications is beyond the scope of this study, but similarities in the physics packages used by MM5 and WRF may provide a starting point to address $T_E$ and $VV_F$ coupling within the MM5 and WRF models. As detailed in section 3 (Tables 2–6), MM5 (MM5 land $R^2 = 0.5$; CI $\neq 0$) and WRF (WRF land $R^2 = 0.2$; CI $\neq 0$) upper-troposphere forecasts have indicated susceptibility to $T_E$ and $VV_F$ coupling over land, suggesting the possibility this anomaly may exist in one or more shared physics packages. JAAWIN MM5 and WRF forecasts utilized the Noah land surface model governing physical processes in MM5 and WRF such as soil and vegetation mediums, evapotranspiration rates, and soil saturation properties, which may not be parameterized correctly (Chen and Dudhia 2001a,b; Hogue et al. 2005; LeMone et al. 2008; Wei et al. 2012). The new Kain–Fritsch cumulus parameterization scheme used by WRF (Table 5; WRF land $R^2 = 0.2$; CI $\neq 0$) saw reduced $T_E$ and $VV_F$ coupling over the Kain–Fritsch cumulus parameterization scheme used by MM5 (Table 5; MM5 land $R^2 = 0.5$; CI $\neq 0$) but still may be inducing incorrect $VV_F$. This may be caused by the dry air minimum entrainment rate incorrectly applied if model humidity levels are biased low, resulting in latent heat flux in the cumulus parameterization schemes (Kain and Fritsch 1990; Siebesma and Holtslag 1996; Derbyshire et al. 2004; Kain 2004; Jonker 2005; de Rooy and Siebesma 2008).

If anomalies in the physics packages remain unaddressed, forecasting of vertical velocity may affect cloud and turbulence prediction decreasing the use of MM5 and WRF in upper-troposphere applications such as aircraft flight planning over sparsely populated regions (i.e., southwest Asia, the Atlantic Ocean, and likely others). If erroneous $VV_F$ areas and intensities are allowed to be forecast along a route of flight an unnecessary lateral deviation to a less desired preplanned flight track may occur resulting in increased time and fuel expenditures. For example, if aircraft operating costs are $5000 per flight hour, an unnecessary deviation of 100 km to avoid areas of incorrectly forecast turbulence may result in a 300-km increase in travel distance and an additional expenditure of $2500 at a cruise speed of 556 km h$^{-1}$. Working toward improving WRF and MM5 upper-troposphere temperature forecasts and eliminating forecast vertical velocity anomalies will help improve air transport operations by reducing unnecessary aircraft deviations resulting in possible economic savings and conservation of resources.

5. Conclusions

This study addressed temperature error and forecast vertical velocity relationships in the upper troposphere where regression analysis provided statistically significant evidence that MM5 and WRF exhibited coupling of temperature error and forecast vertical velocity. MM5 and WRF upper-troposphere temperature forecasts indicated temperature error and vertical velocity coupling between 39° and 59°N at lateral distance deviations up to
100 km from MM5 and WRF modeled flight tracks over land with temperature error and vertical velocity coupling absent over water. Regression analysis suggested different levels of temperature error and vertical velocity coupling in MM5 and WRF upper-troposphere temperature forecasts over different surface elevations above sea level, vegetative surface type, and urban development. Temperature error and vertical velocity coupling in MM5 upper-troposphere temperature forecasts was observed over crop-dominated regions, surface elevations between 300 and 399 m above sea level, and over nonurbanized areas. WRF upper-troposphere temperature forecasts exhibited temperature error and vertical velocity coupling between 0–99- and 300–399-m surface elevation above sea level, over grass/scrub brush, crop regions, and urban areas.

Temperature error and vertical velocity coupling analysis suggests temperature errors may be forcing artificial vertical motion in the MM5 and WRF upper-troposphere forecasts over land. Erroneous prediction of vertical motion by MM5 and WRF in upper-troposphere prediction may lead to incorrect cloud and turbulence forecasts negatively affecting the use of MM5 and WRF for operational decision making such as flight planning. Although the scope of this study was not intended to specifically address algorithms within the physics packages used by MM5 and WRF, it is possible the physics packages shared by MM5 and WRF may need adjustment since temperature error and vertical velocity coupling was observed in both models. Another physical parameter forecast by MM5 and WRF is horizontal wind velocity, which may be subject to forecast vertical velocity coupling resulting in erroneous wind forecasts used during flight planning which causes increased fuel use and increases operating costs. Research into the horizontal wind velocity physical parameter forecast by MM5 and WRF in the upper troposphere could be accomplished using methods explained in this study (e.g., long range in situ measurements, data stratification, and regression analysis) and could likely advance understanding of coupling relationships regarding forecast vertical velocity within MM5 and WRF modeling.

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