Atmospheric Research 132–133 (2013) 278–290

Contents lists available at ScienceDirect

Atmospheric Research

journal homepage: www.elsevier.com/locate/atmos

Thermodynamic and liquid profiling during the 2010 Winter Olympics

R. Ware[a,b,c,*], D. Cimini[d,e], E. Campos[f], G. Giuliani[g], S. Albers[h,i], M. Nelson[a], S.E. Koch[j], P. Joe[k], S. Cober[k]

[a] Radiometrics, 4909 Nautilus Court North, Boulder, CO, USA
[b] National Center for Atmospheric Research, Boulder, CO, USA
[c] Cooperative Institute for Research in the Environmental Sciences, Boulder, CO, USA
[d] Center of Excellence for Severe Weather Forecast, L'Aquila, Italy
[e] Institute of Methodologies for Environmental Analysis, Tito Scalo, Italy
[f] Argonne National Laboratory, Argonne, IL, USA
[g] Abdus Salam International Centre for Theoretical Physics, Strada Costiera, Trieste, Italy
[h] Cooperative Institute for Research in the Atmosphere, Ft. Collins, CO, USA
[i] Earth System Research Laboratory, Boulder, CO, USA
[j] NOAA National Severe Storms Laboratory, Norman, OK, USA
[k] Environment Canada, Meteorological Research Division, Toronto, Canada

ARTICLE INFO

Article history:
Received 4 March 2013
Received in revised form 20 May 2013
Accepted 27 May 2013

Keywords:
Microwave radiometer
Thermodynamic profiler
Liquid (water) profiles

ABSTRACT

Tropospheric observations by a microwave profiling radiometer and six-hour radiosondes were obtained during the Alpine Venue of the 2010 Winter Olympic Games at Whistler, British Columbia, by Environment Canada. The radiometer provided continuous temperature, humidity and liquid (water) profiles during all weather conditions including rain, sleet and snow. Gridded analysis was provided by the U.S. National Oceanic and Atmospheric Administration. We compare more than two weeks of radiometer neural network and radiosonde temperature and humidity soundings including clear and precipitating conditions. Corresponding radiometer liquid and radiosonde wind soundings are shown. Close correlation is evident between radiometer and radiosonde temperature and humidity profiles up to 10 km height and among southwest winds, liquid water and upper level thermodynamics, consistent with up-valley advection and condensation of moist maritime air. We compare brightness temperatures observed by the radiometer and forward-modeled from radiosonde and gridded analysis. Radiosonde-equivalent observation accuracy is demonstrated for radiometer neural network temperature and humidity retrievals up to 800 m height and for variational retrievals that combine radiometer and gridded analysis up to 10 km height.

1. Introduction

Tropospheric thermodynamic (temperature and humidity) and liquid profiles are continuously generated by ground-based microwave radiometer profilers (MPs) operated by national and regional meteorological services. MP distribution is similar to that of radiosondes in Europe, China and Korea and is emerging elsewhere (India, Thailand, the United States, Japan and Columbia). Although instrumented balloon launches (radiosondes) remain the de facto standard

* Corresponding author at: Radiometrics, 4909 Nautilus Court North, Boulder, CO 80302, USA. Tel.: +1 303 449 9192; fax: +1 303 786 9343.
E-mail addresses: ware@radiometrics.com (R. Ware), cimini@imaa.cnr.it (D. Cimini), ecampos@anl.gov (E. Campos), graziano.giuliani@aquila.infn.it (G. Giuliani), steve.albers@noaa.gov (S. Albers), m.nelson@radiometrics.com (M. Nelson), steven.koch@noaa.gov (S.E. Koch), paul.joe@ec.gc.ca (P. Joe), stewart.cober@ec.gc.ca (S. Cober).

0169-8095/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.atmosres.2013.05.019

for upper air monitoring, it is widely recognized that high impact local weather forecasting can be improved using continuous boundary layer thermodynamic measurements (Carbone et al., 2009; Dabberdt et al., 2010; Hoff et al., 2011; Snow et al., 2012; Armstrong et al., 2012).

We present microwave profiler and radiosonde observations by Environment Canada during the 2010 Winter Olympics (Isaac et al., 2012) and numerical gridded analysis provided by the U.S. National Oceanic and Atmospheric Administration. We compare radiometer and six-hour radiosonde thermodynamic soundings during clear, cloudy and precipitating (rain, sleet and snow up to 20 mm/h) conditions. All of the radiometer data are included in the comparison—none were excluded. We also compare radiometer brightness temperature (Tb) observations with brightness temperatures from forward modeled radiosonde soundings and gridded analysis, and neural network, analysis and variational retrieval statistics. This paper extends previous studies of this dataset (Cimini et al., 2011).

2. Instruments and methods

Tropospheric profiles presented in this paper were obtained from a ground-based microwave radiometer profiler (MP), 6-h radiosondes and a numerical weather model gridded analysis. The microwave profiler (Radiometrics MP-3000A) observes 21 K-band (22–30 GHz) and 14 V-band (51–59 GHz) microwave channels at multiple elevation angles, one zenith infrared (9.6–11.5 μm) channel, and surface temperature, humidity and pressure sensors.

The radiometer receives roughly a picowatt of Planck radiation emitted by atmospheric oxygen and water vapor molecules and liquid water, in multiple frequency channels. The atmosphere is semi-transparent in the K-band and lower V-band channels during non precipitating conditions, receiving emission from the atmosphere in addition to cosmic background radiation. The microwave, infrared and surface meteorological observations are automatically converted into continuous temperature, humidity and liquid profiles using radiative transfer equations and neural networks.

2.1. Neural networks

The neural network retrieval method uses historical radiosondes to characterize states of the atmosphere that commonly occur at a particular location. The radiosondes are forward modeled using molecular emission and radiative transfer equations to provide brightness temperatures incident at ground level for each radiosonde sounding. Since radiosonde soundings do not include liquid water (a relatively strong microwave emitter), artificial liquid is included in the radiosonde soundings at levels where humidity is close to saturation (Decker et al., 1978). Four vector neural networks including 26 inputs (8 K-band and 14 V-band microwave channels, an infrared channel, and 3 surface meteorological channels) and 49 hidden nodes generate 58 output nodes (temperature, relative humidity, liquid density and vapor density retrieval heights). Scalar neural networks use the same input and hidden nodes to generate integrated vapor and integrated liquid outputs.

In non-precipitating conditions, neural networks provide temperature and humidity retrievals with accuracy equivalent to observation error typically assigned to radiosonde soundings when they are assimilated into numerical weather models (Kistler et al., 2001; Güldner and Spänkuch, 2001; Cimini et al., 2011). Radiosonde observation error is dominated by representativeness error inherent in characterizing a numerical weather model cell volume by a radiosonde point measurement (Kitchen, 1989), and is roughly an order of magnitude larger than radiosonde point measurement accuracy.

2.2. Zenith and off-zenith retrievals

Thermodynamic and liquid profiles to 10 km height were retrieved from zenith and off-zenith (15° elevation) radiometer observations using neural networks (Solheim et al., 1998). Vertical retrieval intervals are 50 m from the surface to 500 m, 100 m to 2 km, and 250 m to 10 km.

Off-zenith retrievals provide higher accuracy during precipitation by minimizing the affect of liquid water and ice on the radiometer radome. Five years of historical Kelowna, British Columbia (49.93, −119.40, 456 m) radiosondes, adjusted to the radiometer site altitude and to include artificial liquid water profiles, were used for neural network training. The MP was calibrated on December 5, 2009, using liquid nitrogen in a top-mount target. Calibration accuracy of 0.5 K for the top-mount target is verified by Miacci et al., 2013.

2.3. 1DVAR retrievals

One-dimensional variational (1DVAR) methods combining radiometer and numerical weather model gridded analysis outperform other temperature and humidity profiling retrieval methods (Hewison, 2007; Cimini et al., 2010, 2011). 1DVAR combines continuous radiometer observations with satellite and other upper air observations residing in the gridded analysis.

2.4. Radiosondes

Radiosondes (Vaisala RS92-SGP) were launched from the Whistler Valley floor 117 m below and 4.4 km north–northeast of the radiometer to obtain temperature, humidity and wind profiles at 6-h intervals. The Earth System Research Laboratory of the U.S. National Oceanic and Atmospheric Administration (NOAA) provided gridded analysis of Local Analysis and Prediction System (LAPS) temperature, humidity and liquid profiles (Albers et al., 1996). Whistler radiosondes were not included in the LAPS analysis.

Radiometer, radiosonde launch and LAPS analysis grid point locations are indicated in Fig. 1 (adapted from Cimini et al., 2011). Thermodynamic and liquid soundings from the LAPS gridpoint at 700 m altitude were compared with radiometer soundings.

2.5. Other meteorological sensors

The MP and an accompanying suite of meteorological sensors are shown in Fig. 2. Precipitation rate and type,