Chapter 19
Continuous Middle-Atmospheric Wind Profile Observations by Doppler Microwave Radiometry

Rolf Rüfenacht and Niklaus Kämpfer

Abstract Observations of wind profiles in the upper stratosphere/lower mesosphere are challenging as the established measurement techniques based on in situ methods, radars or airglow spectrometers cannot cover this altitude range. Nevertheless, wind information from these altitudes is important for the assessment of middle-atmospheric dynamics in general and as basis for planetary wave or infrasound propagation estimates. Benefitting from recent developments in spectrometers and low-noise amplifiers, microwave radiometry now offers the opportunity to directly and continuously measure horizontal wind profiles at altitudes between 35 and 70 km. This is achieved by retrieving the wind-induced Doppler shifts from pressure broadened atmospheric emission spectra. The typical measurement uncertainties and vertical resolutions of daily average wind profiles lie between 10–20 m/s and 10–16 km, respectively. In this chapter, comparisons of the measured wind profiles to different ECMWF model versions and MERRA re-analysis data are shown. Moreover, the oscillatory behaviour of ECMWF winds is investigated. It appears that the longer period wave activities agree well with the observations, but that the model shows less variability on timescales shorter than 10 days.

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19.1 Introduction

Wind measurements in the range between 35 and 70 km altitude are extremely rare. Despite past initiatives targeting at observations from this altitude range by spaceborne instruments (Hays et al. 1993; Ortland et al. 1996; Baron et al. 2013), to date the only approach providing direct measurements of zonal and meridional wind profiles on a continuous basis is the recently developed technique of ground-based Doppler microwave radiometry. A novel wind lidar technique (Baumgarten 2010) offers better vertical and temporal resolution, but measurements are impossible under overcast sky and can only be obtained with an operator on site. Therefore, such an instrument is not able of delivering a continuous or near-continuous data series. Microwave wind radiometers on the other hand are only marginally affected by weather conditions and their operation can be highly automated what makes it possible to provide uninterrupted time series of middle-atmospheric zonal and meridional wind on a routine basis.

19.2 The Measurement Technique

Wind radiometers passively observe atmospheric emissions originating from rotational transitions of molecules. As the frequency of the emitted photons is governed by the quantum mechanical selection rules, the emission frequency ν_0 is sharply defined. In the event of a non-zero line-of-sight wind component v_{LOS}, the signal is Doppler shifted in frequency by

$$\delta\nu = \frac{v_{\mathrm{LOS}}}{c} \cdot \nu_0, \tag{19.1}$$

where c denotes the speed of light.

Moreover, the emission process is affected by collisions with other molecules what leads to the effect of pressure broadening of the spectral line. Therefore, the signal on the wings of the emission spectrum, far away from ν_0, predominantly originates from high-pressure environments, whereas the line peak in the vicinity ν_0 is dominated by emissions under low-pressure conditions. As the vertical pressure profile of the atmosphere is accurately known, this effect can be exploited to derive altitude-dependent wind information from spectrally resolved measurements of microwave radiation.

The effect of wind at different altitudes on the atmospheric emission spectra is illustrated in Fig. 19.1. It should, however, be noted that this figure shows the situation for unrealistically high wind speeds. In practice, the challenge lies in determining a tiny Doppler shift in the order of less than 10^{-7} of the observation frequency. The used heterodyne-type receivers thus need to feature a high spectral resolution, high-frequency stability, and low receiver noise.

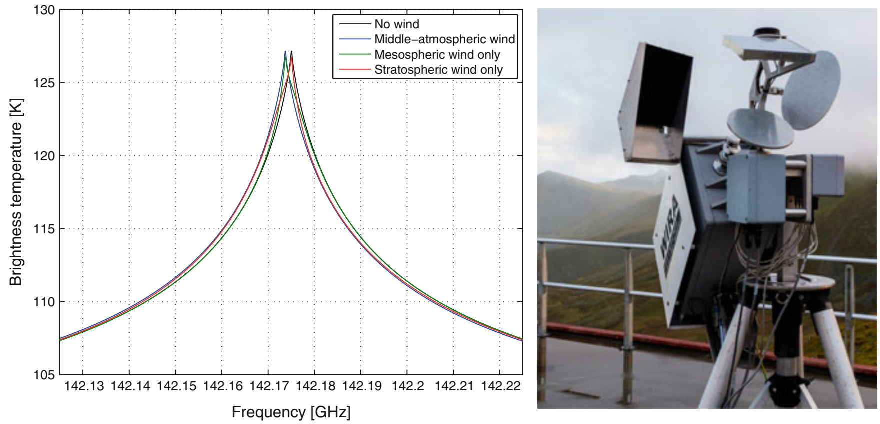

Fig. 19.1 **left:** Illustration of the effect of wind at different altitudes on ozone emission spectra as observable by ground-based radiometers at 142 GHz. For demonstration purposes, a wind speed of 3000 m/s has been chosen for these simulations which is far off any realistic values. The maximum wind speed in the middle atmosphere is generally below 150 m/s. **right:** The wind radiometer WIRA in operation in cloudy conditions

The mentioned frequency requirements can be achieved by the use of state-of-the-art Fourier transform spectrometers and stable local oscillator frequency references produced by actively multiplied synthesiser signals or Gunn oscillators phase locked to an oven-controlled quartz or GPS frequency normal. The receiver signal-to-noise ratio can be highly improved by the integration of high-frequency low-noise amplifiers and sideband filters on the radio frequency (RF) side of the mixer. Owing to recent developments in semiconductor technology, such amplifiers have become available at frequencies suitable for wind radiometry. Lower noise levels could be achieved by using cryogenic receiver electronics. The price for the higher sensitivity would, however, be a loss in autarchy, weathering resistance and transportability of the instrument what might be supportable for laboratory instruments but excludes this option for campaign radiometers. For the determination of the wind profiles from the measured radiation spectra, the atmospheric radiative transfer model is inverted by using the optimal estimation technique (Rodgers 2000). A detailed description of optimal estimation wind profile retrievals from ground-based microwave radiometers including the assessment of measurement uncertainties can be found in Rüfenacht et al. (2014), Rüfenacht and Kämpfer (2017), Rüfenacht et al. (2019).

Worldwide, there are currently three ground-based microwave radiometers capable of wind profile retrievals (Rüfenacht et al. 2012; Hagen 2015; Fernandez et al. 2016). They provide continuous observations of daily average wind profiles between altitudes of 10 and 0.01 hPa (approx. 35–70 km) with typical uncertainties ranging from 10 to 20 m/s and vertical resolutions between 10 and 16 km. A picture of such an instrument is shown in Fig. 19.1.

19.3 Observations of Zonal and Meridional Wind

From the three existing radiometers capable of Doppler wind measurements, the ground-based receiver WIRA (Rüfenacht et al. 2012, 2014) has acquired most observational data. Between 2010 and 2015, it has been measuring at four stations located at high (Sodankylä at 67°22’ N, 26°38’ E), mid (Bern at 46°57 N, 7°26 E and Observatoire de Haute-Provence at 43°56’ N, 5°43’ E) and low latitudes (Observatoire du Maïdo, La Réunion at 21°04’ S, 55°23’ E). Figures 19.2 and 19.3 display the time series of zonal and meridional wind profiles as measured by WIRA during these campaigns. The grey horizontal lines identify the upper and lower limit of the altitude range within which the measurements are judged trustworthy (according to conditions defined in Rüfenacht et al. 2014). Meridional wind measurements are only available since a major instrumental upgrade in autumn 2012. In Figs. 19.2 and 19.3, the most prominent data gaps originate from down periods of the instrument (due to a tropical cyclone necessitating the dismounting of the instrument, a loose connector, etc.). Apart from these few interruptions, the figures illustrate the long-term continuity which can be achieved by wind radiometer observations even under adverse

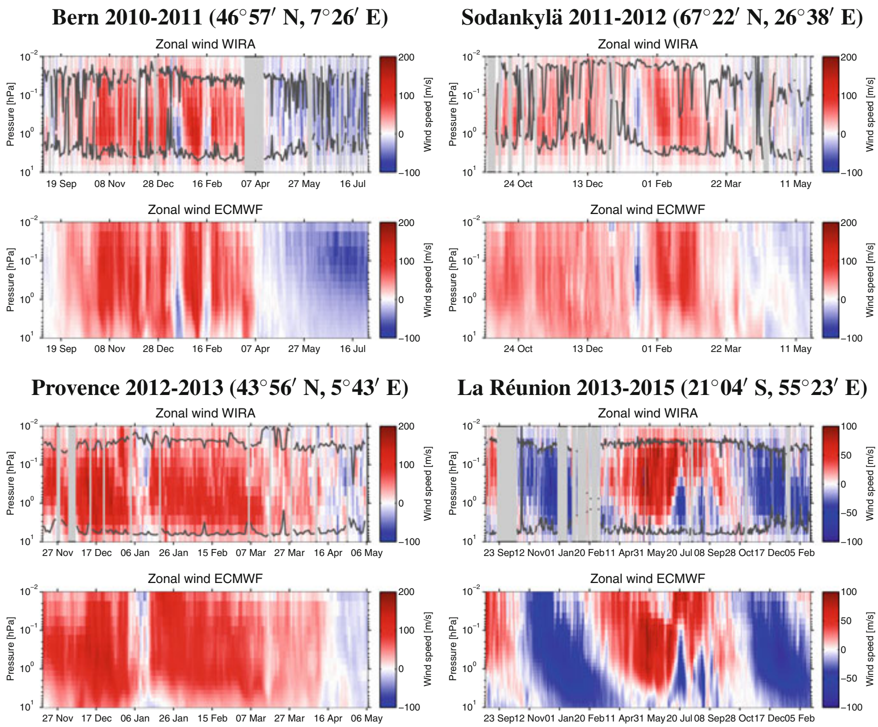

Fig. 19.2 Zonal wind profiles measured by WIRA in comparison with ECMWF operational analysis data

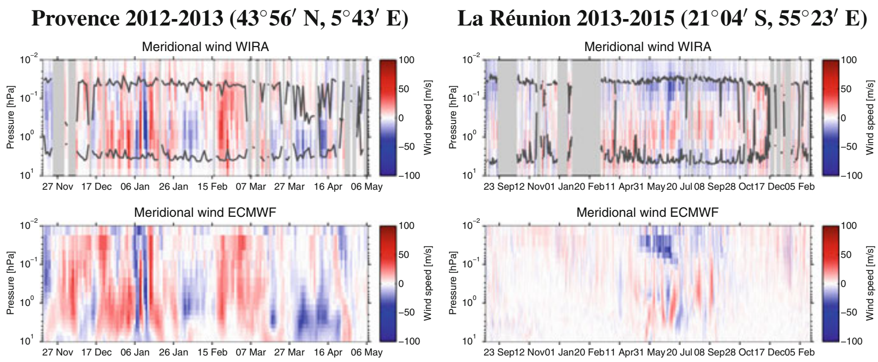

Fig. 19.3 Meridional wind profiles measured by WIRA in comparison with ECMWF operational analysis data

weather conditions. Due to the relatively long wavelength of microwave radiation, measurements remain possible under overcast skies or in the event of frozen precipitation, only particularly strong tropospheric attenuation caused by high liquid water contents in the presence of rain or thick liquid water clouds can temporarily suspend the observations. Moreover, a high degree of automation of microwave radiometers can be achieved.

19.3.1 Comparing Wind Radiometer Observations to General Circulation Models

The continuous nature of the observations and the fact of being unbiased to certain weather patterns make wind radiometers ideal tools for assessing the quality of middle-atmospheric dynamics in global circulation models (GCM). Such assessments are not only of interest in order to uncover possibilities for further model developments. Due to the scarcity of wind measurements in the middle atmosphere, the background wind for calculating the propagation of infrasound or gravity waves is usually taken from some GCMs.

Operational analysis data from the GCM of the European Centre for Medium-Range Weather Forecasts ECMWF (ECMWF 2017) are plotted in the panels below the radiometer observations in Figs. 19.2 and 19.3. They agree well with the observations in the larger structures such as the annual cycle for the mid- and high latitude stations or the mixed influence of the semi-annual oscillation and annual cycle for La Réunion. Even shorter, highly dynamical features such as the wind reversals associated with sudden stratospheric warmings or vortex displacement events are relatively well captured.

For quantitative comparisons between models and radiometer observations, the model data should be convolved with the averaging kernels of the radiometer

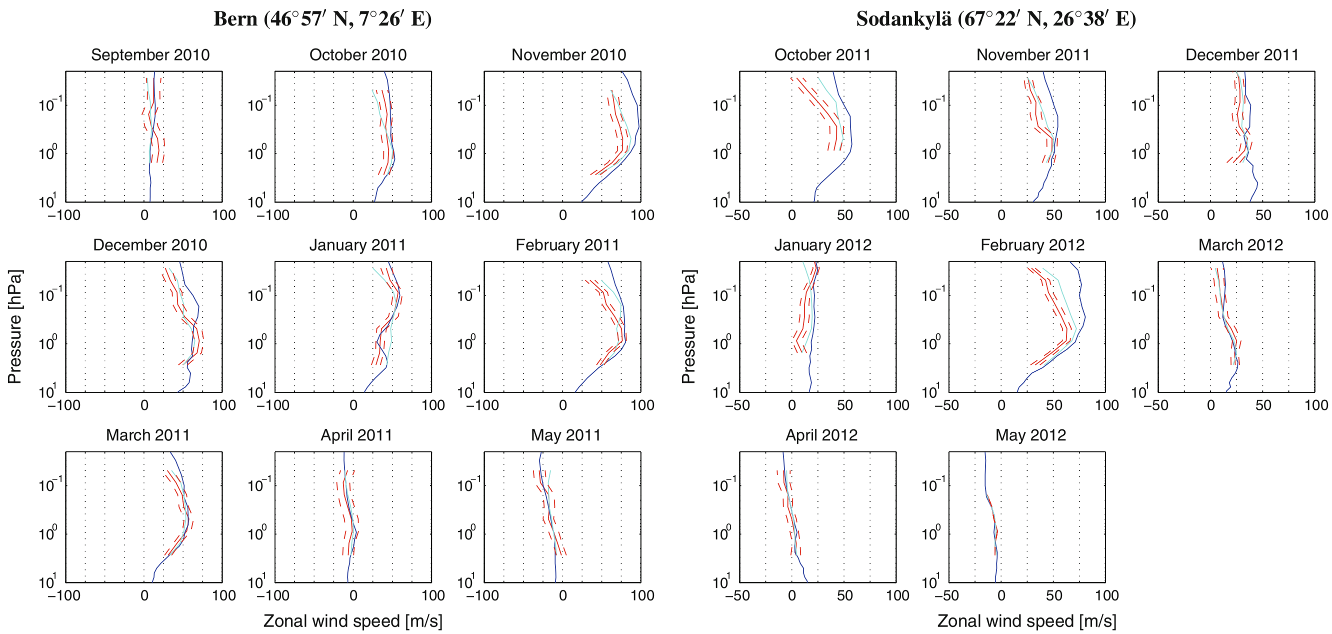

Fig. 19.4 Monthly averaged zonal wind profiles (median) from WIRA along with their random error (red), model data from ECMWF operational analysis (blue) and ECMWF data convolved with WIRA's averaging kernels (cyan). These panels present data from the Bern and Sodankylä campaigns which were obtained with the first operational version of the instrument. The panels in the continuation of the figure on the next page show the observations from the Provence and La Réunion campaigns which were obtained with an upgraded version of the receiver

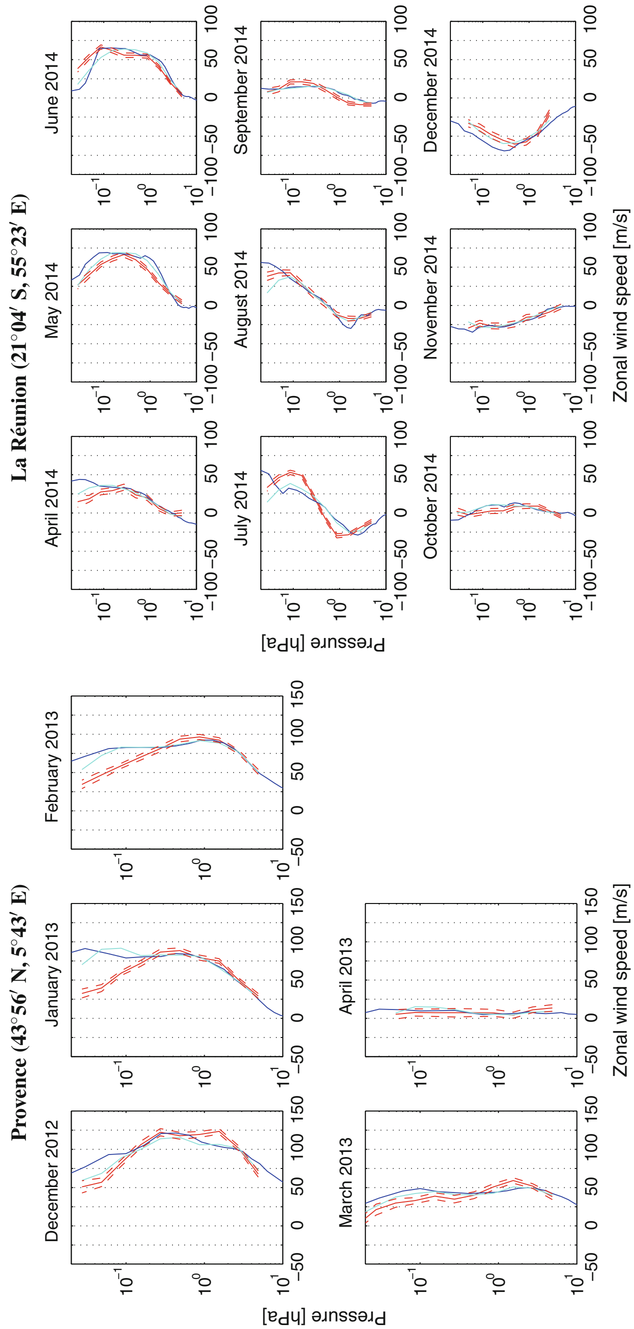

Fig. 19.4 (continued)

measurements (Rodgers 2000), in order to account for the limited altitude resolution of the measurements. Moreover, artificial data gaps have been added to the model data at altitudes and times where WIRA was not able to provide measurements. Model data treated in this way are directly comparable to the observations. Monthly averages of zonal wind from ECMWF and WIRA are compared in Fig. 19.4. Convolved model data and observations generally agree within their errors. Notable exceptions are the higher ECMWF absolute wind speeds at mesospheric altitudes which occur during certain months at mid- and high latitudes. These are especially present in the observations from Provence. This period is investigated in more detail in Fig. 19.5. In addition to the data from ECMWF 37r3 being the observational version by this time, data from ECMWF 38r1 are shown. The major upgrade from ECMWF from 37r3 to 38r1 which comprised among others the increase from 91 to 137 model levels had drastically reduced the mesospheric discrepancy in temperature between model data and lidar observations (Le Pichon et al. 2015). Similarly, for zonal wind, the discrepancy is significantly reduced. However, the winds in the model remain slightly stronger than in the observations. In contrast, the MERRA re-analysis of the GEOS-5 general circulation model (Rienecker et al. 2011) rather indicates lower zonal wind speeds than measured by WIRA. No definite tendency for under or overestimation could be established for the meridional winds.

19.4 Assessment of Oscillation Activity

Waves and oscillations play a fundamental role in the dynamics of the middle atmosphere. Thanks to the continuous nature of the observations by wind radiometry, such periodicities can be assessed. In a study on long-period oscillations in the middle-atmospheric zonal and meridional wind field (Rüfenacht et al. 2016), observations from WIRA have been compared to ECMWF model data. The results are summarised in Figs. 19.6 and 19.7 showing time series of oscillation amplitudes at the stratopause for WIRA and ECMWF. This altitude has been chosen because wind speeds tend to reach their middle-atmospheric maximum at this level and because the average winds of ECMWF and WIRA agree well in this region.

Obviously, observations and model capture the same dominant periodicities. The agreement on the timing of the peaks in oscillation activity at the different periods is excellent. Nevertheless, ECMWF appears to incorporate lower oscillation amplitudes in comparison with WIRA. Moreover, variations at periods shorter than about 10 days are less present in the model data. This fact cannot fully be explained by the presence of measurement noise but might be related to some modelling issues. Similarly, Le Pichon et al. (2015) had reported on the underestimation of the short periodicities in ECMWF's middle-atmospheric temperature field at lidar observation sites in Europe and North America.

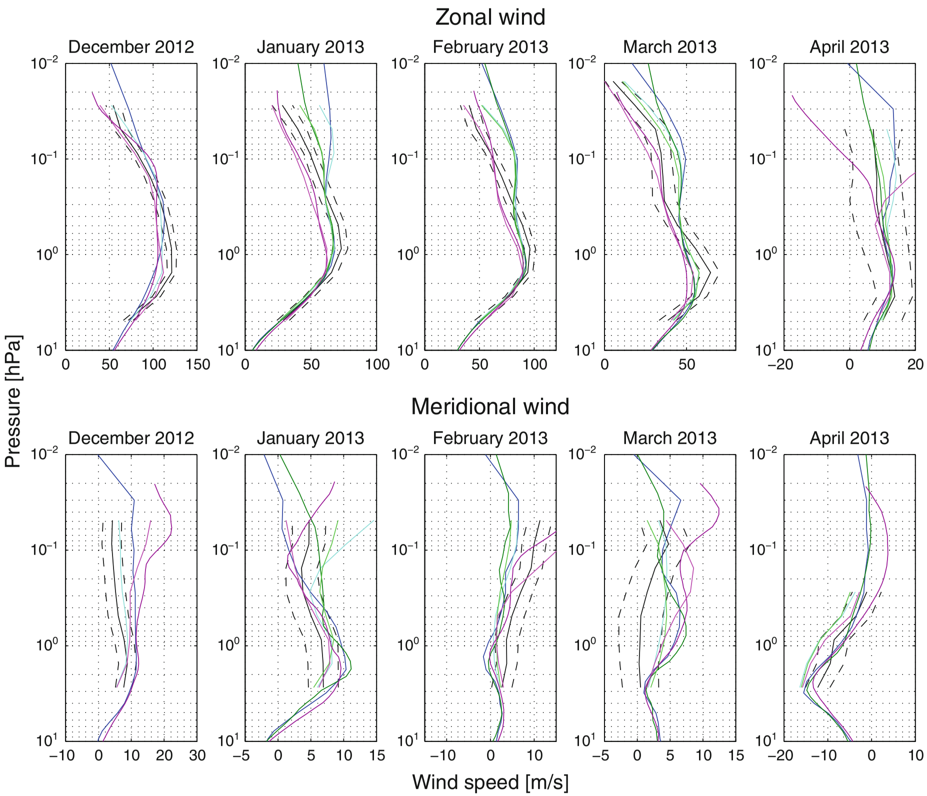

Fig. 19.5 Zonal and meridional monthly average wind profiles for the measurement campaign at Observatoire de Haute-Provence. Observations by WIRA in black (with the corresponding random error represented by dashed lines) compared to model data from ECMWF version 37r3 (blue), ECMWF version 38r1 (green) and MERRA (pink). The lines with darker shading represent the original model data. The brighter lines correspond to the model data convolved with WIRA's averaging kernels and with data gaps introduced for altitudes and times where WIRA has no measurement point

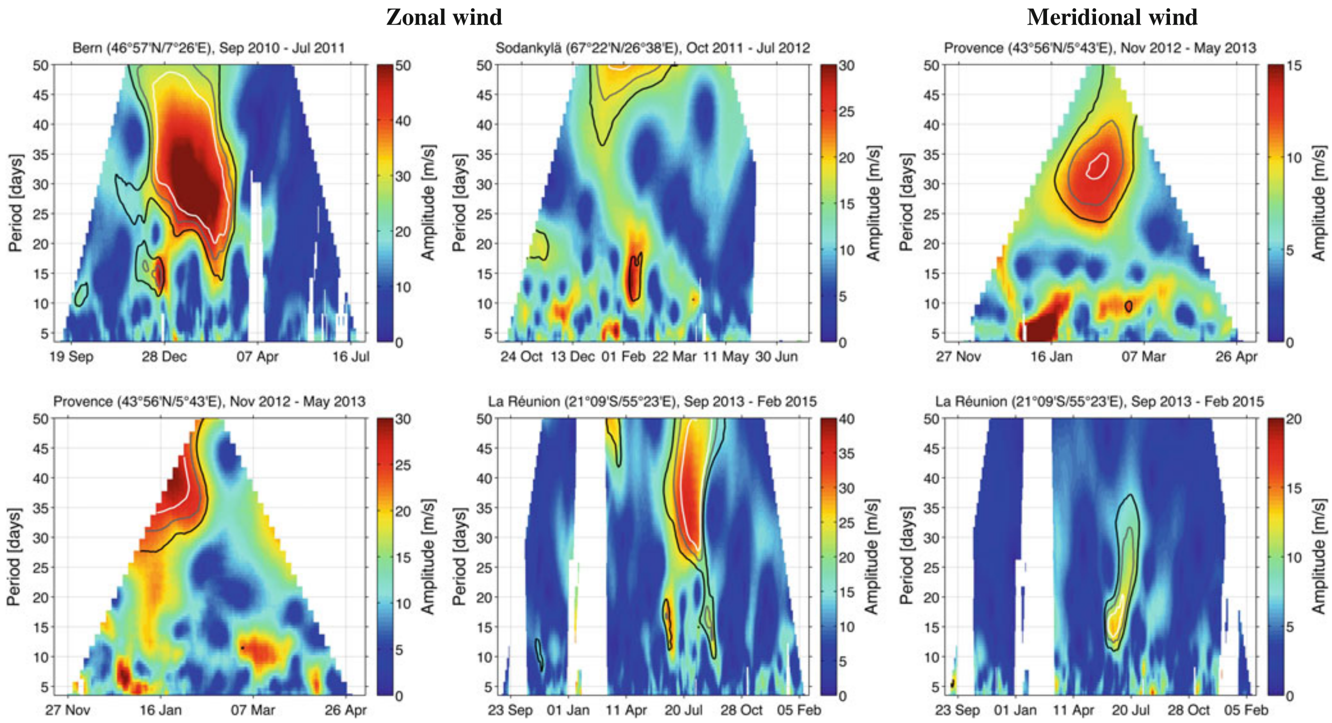

Fig. 19.6 Time series of long-period oscillation activity in zonal and meridional wind at 0.9 hPa measured by WIRA. The black, grey and white contour lines mark the false alarm probabilities of $\alpha = 0.5$, 0.1 and 0.01

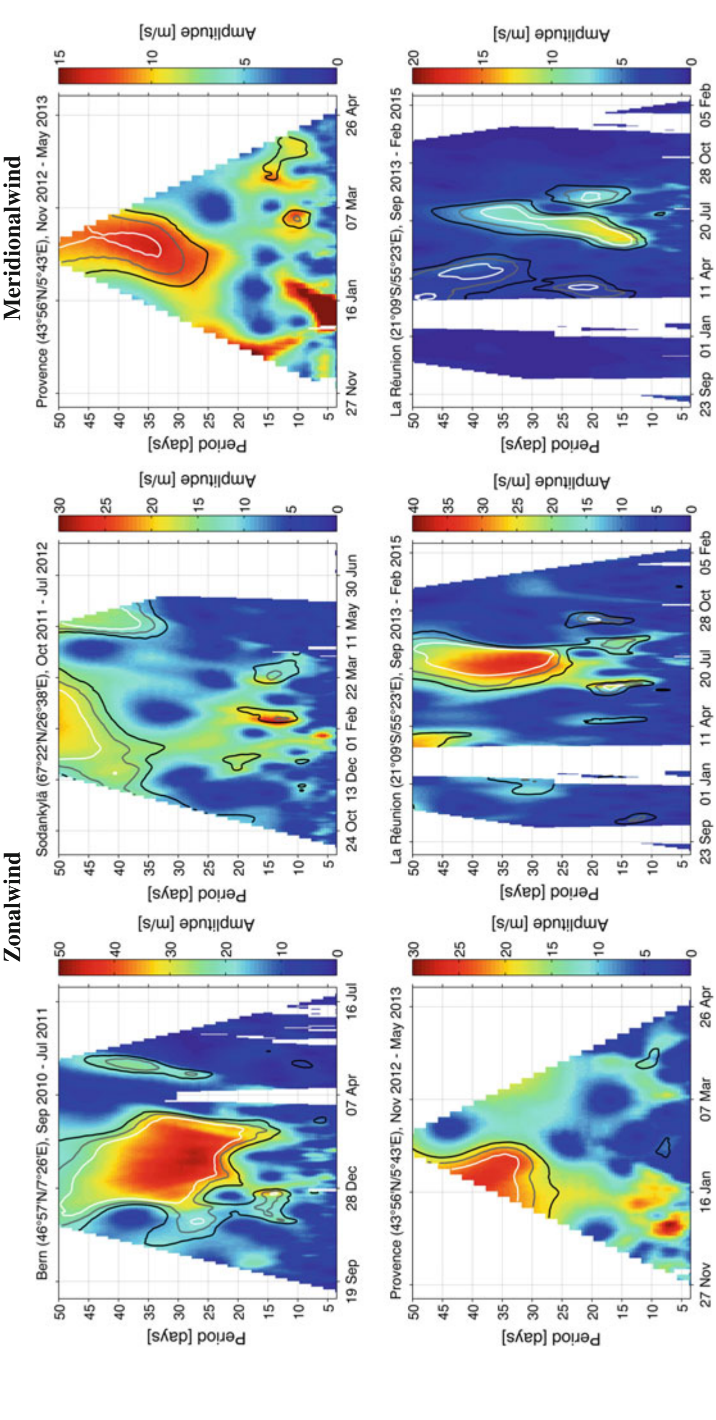

Fig. 19.7 As Fig. 19.6 but for ECMWF profiles convolved with WIRA's averaging kernels and with data gaps introduced where WIRA did not provide reliable measurements

19.5 Conclusions

The novel measurement technique of ground-based Doppler microwave radiometry has proven to be a reliable tool for the assessment of horizontal winds between 35 and 70 km altitude, where observations are extremely rare. Near-continuous time series of observations can be recorded due to the relative transparency of clouds and frozen precipitation to microwave radiation and thanks to the possibility of operating radiometers in a highly automated way. Wind radiometer measurements are valuable for the evaluation of the middle-atmospheric wind field of numerical weather prediction models. Observations from the wind radiometer WIRA have been compared to ECMWF model data showing good agreement in the stratosphere with occasional overestimation of the modelled zonal wind in the mesosphere. The timing of long-period oscillations at stratopause level agrees very well between WIRA and ECMWF but the oscillation amplitudes for ECMWF tend to be lower and less variability at periods shorter than 10 days is present in the model data.

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