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Modelling of annual variation of tropospheric moisture in the Australian region from radiosonde and satellite data

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Radiosonde observations of tropospheric water vapour in the Australian region over several decades by the Australian Bureau of Meteorology provide data suitable for modelling the annual variation of moisture at standard pressure heights. The augmentation of this data bank in recent years with satellite observations allows such modelling to be extended to more locations. The climatic models of tropospheric water vapour derived in this paper are shown to have useful predictive capabilities at low altitudes, where the water vapour is most concentrated. The predictive capability decreases in usefulness at higher altitudes where the air is drier.

Introduction

The transport in the earth's troposphere of water in its various forms dominates the processes which stabilise the temperature of the earth's surface and adjacent air. The vertical distribution of water vapour in the troposphere has been studied extensively using radiosonde techniques. The distribution has been modelled by Siessenwine et al. (1968) using radiosonde data for the equatorial, mid-latitude and polar regions during summer and winter. However, these models are insufficient to describe fully the complex spatial and temporal variations observed.

Propagation of electromagnetic radiation in the troposphere is affected by the distribution of water vapour. At radio wavelengths, waves are refracted by gradients in the atmospheric refractive index which depends in part on the partial pressure of water vapour. At infrared and millimetre wavelengths, radiation is absorbed by water vapour and other atmospheric constituents. Thus, the spatial and temporal distribution of water vapour in the troposphere is needed for models of the propagation of electromagnetic radiation.

In the Australian region, detailed atmospheric moisture data derived from radiosonde observations from 1953 to 1975 are presented by Maher and McRae (1966) and Maher and Lee (1977). However, these data are not in the form of a general model.

This paper describes the characteristics of the available radiosonde and satellite data and the models derived from these data. The present work makes use of an analysis of three-hourly surface mixing-ratio data described by Dunsmuir and Phillips (1990), which will be referred to as Paper A.

The models

The aim of the present analysis is to estimate the parameters in two climatic models: one of the mean mixing ratio, the other of the standard deviation of the residual variation. The model for the mean provides an estimate of the expected mixing ratio at a given location, date and time. The model for the standard deviation provides an estimate of the uncertainty in the expected mixing ratio (due, for example, to the passage of evolving weather systems or to errors in the observations on which the models are based). The parameters are esti-

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mated for both radiosonde and satellite data at each of the locations studied, and at each pressure height for which data were available.

The model for mixing ratio at each location and pressure height is assumed to be of the form used in Paper A in the analysis of three-hourly surface data, namely

$$x_{ydh} = \mu(d,h) + e_{ydh}, \qquad \ldots 1$$

where x_{ydh} is the mixing ratio value observed in year y, date d, and time h where h spans eight equally-spaced time points over the 24-hour interval and $h = 0$ corresponds to 2300 UTC.

The climatic average mean term $\mu(d,h)$ and the standard deviation $\sigma(d,h)$ of the residual e_{ydh} are modelled by Eqns 2 and 3 in Paper A, namely:

$$\begin{aligned}\mu(d,h) = \beta_0 &+ \beta_1 \cos(2\pi d/365) + \beta_2 \sin(2\pi d/365)\\ &+ \beta_3 \cos(4\pi d/365) + \beta_4 \sin(4\pi d/365)\\ &+ \beta_5 \cos(2\pi h/8) + \beta_6 \sin(2\pi h/8)\\ &+ \beta_7 \cos(2\pi d/365) \cos(2\pi h/8)\\ &+ \beta_8 \cos(2\pi d/365) \sin(2\pi h/8)\\ &+ \beta_9 \sin(2\pi d/365) \cos(2\pi h/8)\\ &+ \beta_{10} \sin(2\pi d/365) \sin(2\pi h/8) \qquad \ldots 2\end{aligned}$$

and

$$\begin{aligned}\sigma(d,h) = \delta_0 &+ \delta_1 \cos(2\pi d/365) + \delta_2 \sin(2\pi d/365)\\ &+ \delta_3 \cos(2\pi h/8) + \delta_4 \sin(2\pi h/8). \qquad \ldots 3\end{aligned}$$

These models express the mean mixing ratio in terms of an overall constant, annual and semi-annual cycles, a diurnal cycle and annual modulation of the diurnal cycle, and the standard deviation of the fluctuations around the mean in terms of an overall constant, an annual cycle, and a diurnal cycle.

Because the radiosonde measurements are available only once daily (at 2300 UTC) the diurnal and annual-diurnal interaction components used for the three-hourly model in Paper A, namely $\beta_5, \ldots, \beta_{10}$ in Eqn 2 and δ_3, δ_4 in Eqn 3, cannot be estimated from those data. Consequently, at each of the eight available pressure heights designated by p ($= 0, \ldots, 7$) a fit is made to the simpler model

$$x_{ydp} = \mu^R(d,p) + e_{ydp}, \qquad \ldots 4$$

where x_{ydp} is the mixing ratio observed in year y, on day d and at pressure height p, and where

$$\begin{aligned}\mu^R(d,p) = \beta_0{}^R(p)&\\ &+ \beta_1{}^R(p) \cos(2\pi d/365)\\ &+ \beta_2{}^R(p) \sin(2\pi d/365)\\ &+ \beta_3{}^R(p)\cos(4\pi d/365)\\ &+ \beta_4{}^R(p) \sin(4\pi d/365). \qquad \ldots 5\end{aligned}$$

Here, the superscript R is used to designate the model derived from radiosonde data; later the superscripts G and S will be used to designate ground and satellite parameters respectively. The model for standard deviation is likewise simplified to

$$\begin{aligned}\sigma^R(d,p) = \delta_0{}^R(p) + \delta_1{}^R(p) \cos(2\pi d/365) &+\\ \delta_2{}^R(p) \sin(2\pi d/365). &\qquad \ldots 6\end{aligned}$$

The radiosonde parameters of Eqns 5 and 6 at ground level ($p = 0$) are not all directly comparable with the parameters of the full three-hourly ground model in Paper A, because some include the diurnal component at 2300 UTC. Indeed, each of the parameters $\beta_0{}^R(0)$, $\beta_1{}^R(0)$, $\beta_2{}^R(0)$, and $\delta_0{}^R(0)$ is equivalent to the sum of two parameters in the three-hourly ground model.

The satellite mixing-ratio measurements, derived from retrievals of TOVS (TIROS Operational Vertical Sounder) data from the NOAA (National Ocean and Atmospheric Administration) series of satellites, are available twice daily at most locations from each satellite. The values used are averages of all retrievals during a given pass within a 300 kilometre radius of the required location that are not affected by cloud. The time at which the average is reported is the average time of the readings used. In order to get the most accurate average retrieval on a given day, the pass yielding the largest number of retrievals unaffected by cloud was selected. This average is usually not at 2300 UTC (the radiosonde flight time). Accordingly, a correction needs to be made to bring the model parameters into line with the radiosonde parameters.

At ground station locations, satellite retrievals can be adjusted to 2300 UTC using Eqns 2 and 3.

At maritime locations lacking ground stations, satellite retrievals are also adjusted to 2300 UTC using Eqns 2 and 3 but the diurnal and interaction parameters are not known and must therefore be estimated. The procedure for estimating the unknown parameters uses Eqns 6 and 7 in Paper A.

Characteristics of data

Modelling tropospheric moisture, as is clear from the previous section, requires not only daily radiosonde and satellite measurements but also three-hourly surface data. The latter are required to adjust satellite data to 2300 UTC and to supply diurnal and interaction parameters, which cannot be determined directly from daily data.

The main features of the three sources of data are as follows. Radiosonde measurements at 31 recording stations operated by the Bureau of Meteorology in the Australian region, at eight standard pressure heights (viz. surface, 900, 850, 800, 700, 600, 500, 400 hPa) and at 2300 UTC, were obtained for the ten-year period from 1 January 1974 to 31 December 1983. The inherently high spatial and temporal variability associated with the tropospheric moisture field limits the accuracy of point measurements, for example with radiosondes, in representing the average moisture field over a spatial and temporal domain (see Nash et al. 1985).

Surface mixing-ratio data, at three-hourly intervals, were obtained at the 31 radiosonde sites for the same ten-year period.

Satellite measurements in the form of NOAA TOVS data have been routinely captured by the Bureau of Meteorology since 1983. A description of the Australian operational system for remotely sensed meteorological data, which was used to produce the data analysed in the present study, is given by Kelly et al. (1983). Moisture profiles were derived from two instruments in the TOVS package: the High resolution Infrared Radiation Sounder (HIRS), sampling at 20 infrared frequencies, and the Microwave Sounding Unit (MSU), sampling at four microwave frequencies. Both instruments scanned a 2250 km wide swath, the HIRS with a 17 km diameter field of view and the MSU resolving a 110 km diameter circle. Inconsistencies between HIRS and MSU retrievals were used to indicate cloud contamination.

Satellite retrievals of mixing ratio derived from NOAA TOVS data were available at only five of the eight standard radiosonde pressure heights (viz. surface, 850, 700, 500, 400 hPa) and at variable times. The Bureau of Meteorology applied spatial filtering and corrections for cloud contamination to produce moisture (and temperature) profiles with an average spacing of 60 km. Satellite data were obtained from 63 locations, 29 of which matched radiosonde sites, for the single year from 1 December 1983 to 30 November 1984. The intercomparisons of satellite retrievals of precipitable water reported by Le Marshall (1988) indicate that rms differences commonly represent between 30 and 40 per cent of the total precipitable water.

A pilot study of the radiosonde data revealed a pattern of missing observations — particularly before 1982, and during the winter months at the higher levels when the values are low. The explanation became apparent after discussion with the Bureau of Meteorology. Before 1982, mixing ratio was measured with a Lithium Chloride sensor, which could not measure low values of humidity or any humidity value when the temperature was below −40°C. During 1982, use of a more sensitive carbon element commenced. By averaging the available data for each day of the year over the ten-year period analysed, the effect of missing data was minimised.

The pilot study also confirmed that, as with the surface model, there was a need to include the semi-annual component in Eqn 5 at levels above the surface.

Fitting models to radiosonde data

The models at Eqns 5 and 6 for mixing-ratio mean and standard deviation were estimated, at each pressure height separately, using the ten-year averaging procedure outlined below and discussed more fully in Paper A.

The first step in fitting the mean mixing-ratio model described by Eqns 4 and 5 at a given pressure height and site was to form the ten-year averages:

$$\bar{x}_{dp} = (1/n_{dp})\, \Sigma_y\, x_{ydp}, \qquad \ldots 7$$

where n_{dp} is the number of years for which data are available on day d at pressure height p over all such years in the ten-year period. Since $\bar{x}_{dp}$ has the same mean term, $\mu^R(d,p)$ for all values of d, the model parameters $\beta_0{}^R(p)$ ..., $\beta_4{}^R(p)$ could be fitted by least squares regression using the $\bar{x}_{dp}$, $d = 1, \ldots, 365$.

The parameters in the standard deviation model at Eqn 6 were estimated as follows. First, the standard deviation of the residuals between the averaged data $\bar{x}_{dp}$ and the estimated model $\hat{\mu}^R(d,p)$ was calculated for each month k, namely

$$SD_k[\bar{x}_{dp} - \hat{\mu}^R(d,p)].$$

Then, assuming the standard deviation of the residuals of the averaged data to be

$$SD[\bar{e}_{dp}] = \sigma^R(d,p)/n_{dp}{}^{1/2},$$

the standard deviation of the original data for each month k was estimated from

$$\hat{\sigma}_{kp} = \bar{n}_{kp}{}^{1/2}\, SD_k[\bar{x}_{dp} - \hat{\mu}^R(d,p)], \qquad \ldots 8$$

where $\bar{n}_{kp}$ is the average value of n_{dp} in month k. Finally, the parameters $\delta_0{}^R(p), \ldots, \delta_2{}^R(p)$ were obtained by fitting the $\hat{\sigma}_{kp}$ using least squares regression to the monthly analogue of model at Eqn 6:

$$\sigma^R(k,p) = \delta_0{}^R(p) + \delta_1{}^R(p) \cos(2\pi(k-0.5)/12) + \delta_2{}^R(p) \sin(2\pi(k-0.5)/12). \qquad \ldots 9$$

When the model was fitted to data from the 31 radiosonde recording stations at each pressure height, the explanatory power of the model was assessed by evaluating the R^2 statistic (e.g. see Harvey (1981) for the definition). R^2 is the ratio of the sum of squares due to the regression to the total sum of squares, with an adjustment for degrees of freedom, expressed as a percentage. A high R^2 value indicates a model that successfully predicts a large proportion of the observed variation.

The R^2 values for the fitted mean model at Eqn 5 at the different pressure heights exhibited median values over the 31 radiosonde stations ranging from about 90 per cent at the surface to about 50 per cent at the highest altitude (400 hPa). For the fitted standard deviation model at Eqn 6, the medians of the R^2 values lay between 50 per cent and 65 per cent at all altitudes. These results indicate that for mean mixing ratio the fit is good at the surface ranging to acceptable at the upper

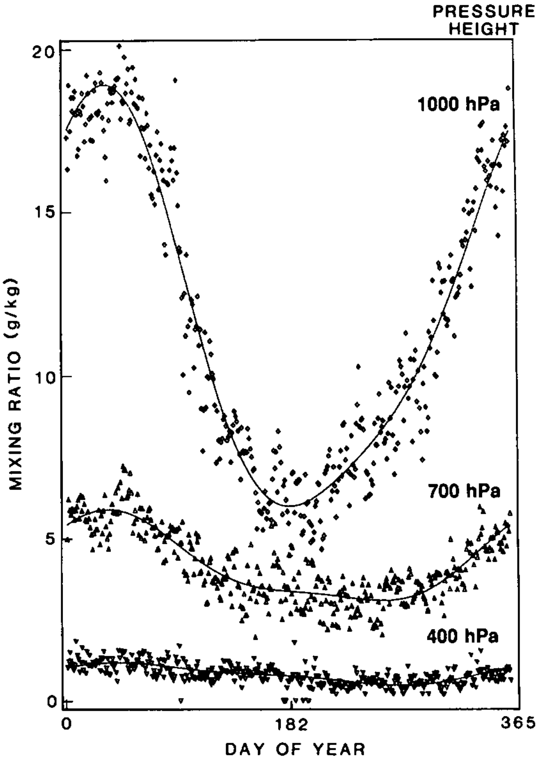


Fig. 1 **Annual variation of actual and predicted mixing ratio for three pressure heights at Port Hedland.**

levels. For standard deviation, the fit is acceptable at all levels.

An illustration of the fit achieved by this model is provided by Fig. 1, which shows data from Port Hedland at the three pressure heights 1000, 700 and 400 hPa. At each pressure height, both the fitted model and the ten-year averaged daily data are given. Compared with other stations studied, the Port Hedland model is among the best fitted at 1000 hPa, better than average at 700 hPa, and poorer than average at 400 hPa.

Fitting models to satellite data

The model described by Eqns 4 to 6 was also used for the satellite retrievals although instead of the 365 days of ten-year averages used to fit the radiosonde retrievals, only 365 individual readings from a one-year span are available. In order to match the satellite data to a calendar year, a day of the year index d was calculated from the day of each retrieval. Then, the model at Eqn 7 was fitted at each available pressure height p to the satellite retrievals to obtain estimates of $\beta_0''(p), \ldots, \beta_4''(p)$ where the double prime is used to designate raw satellite parameters, which must be corrected as explained below. The monthly standard deviations of the residuals were calculated in order to estimate $\delta_0''(p), \ldots, \delta_2''(p)$ in the same manner as for the radiosonde data.

Because the diurnal component of the surface model is substantial (see Paper A), the fitted parameters will be biased unless adjustment is made for the fact that the satellite soundings are made at times usually different from 2300 UTC. The effects on the annual and semi-annual components are small and ignored. However, the set of constants $\beta_0''(p)$ and $\delta_0''(p)$ are substantially altered by changing the time h'' at which the recordings are made. These parameters were therefore adjusted at each pressure height p to obtain values at 2300 UTC defined by

$$\begin{aligned}\beta_0'(p) = \beta_0''(p) + \{&\beta_5^G - \beta_5^G \cos(2\pi h''/8)\\ &-\beta_6^G \sin(2\pi h''/8)\}\\ &\beta_0''(p)/\beta_0''(0)\end{aligned} \qquad \ldots 10$$

and

$$\begin{aligned}\delta_0'(p) = \delta_0''(p) + \{&\delta_3^G - \delta_3^G \cos(2\pi h''/8)\\ &-\delta_4^G \sin(2\pi h''/8)\}\\ &\delta_0''(p)/\delta_0''(0)\end{aligned} \qquad \ldots 11$$

The single prime is used to designate satellite parameters corrected to 2300 UTC but lacking the further correction described in the next section.

The values of β_5^G, β_6^G, δ_3^G, δ_4^G needed for the corrections (Eqns 10 and 11) were obtained in two ways. For satellite measurements at locations matched to surface stations, the actual values were used. For unmatched satellite measurements, predictions were made using the fitted values $\beta_j''(0)$ and $\delta_j''(0)$ in Eqns 6 and 7 in Paper A, for example:

$$\beta_5^G = A_5 + \Sigma_{j=0}^{4}\ a_{5j}\ \beta_j''(0) + a_{55}\,\lambda,$$

where λ is the latitude measured in degrees south of the equator. At pressure heights above the surface (i.e. $p>0$), diurnal terms are not known and must be assumed. The factors $\beta_0''(p)/\beta_0''(0)$ and $\delta_0''(p)/\delta_0''(0)$ reflect the assumption that diurnal components are in phase at all pressure heights but reduce in amplitude proportionally with the average values $\beta_0''(p)$ and $\delta_0''(p)$.

The goodness of fit of the model to the satellite data was assessed by calculating the R^2 statistic, as it was with the radiosonde data (described in the previous section). For the fitted mean model, the medians of the R^2 values over the 63 satellite locations ranged from about 30 per cent at the surface to about 5 per cent at the 400 hPa level. For the fitted standard deviation model, the medians of the R^2 values lay between about 20 per cent and 40 per cent at all altitudes. At some locations, the fitted mean model is acceptable at all altitudes (with R^2 values over 20 per cent at all levels); overall, however, the fit for means ranges from barely acceptable at the surface to poor at the high levels. For standard deviations, the fit is just acceptable at all levels. The poor fit for means indicates that a single year's data are inadequate to establish climatic averages with acceptable precision at all levels. Nevertheless, the parameters fitted to the satellite data provide valuable information in regions where radiosonde measurements are lacking.

Calibrating satellite parameters to radiosonde parameters

An initial study of radiosonde and satellite retrievals indicated the presence of biases between the measurements from the two sources. This initial study was based upon the 'matched data' used by the Australian Bureau of Meteorology to monitor the calibration between the radiosonde and satellite retrievals. Statistically significant biases exist at many locations and are different in winter and summer.

At least two sources of bias are possible. Firstly, biases could be due to the TOVS retrieval scheme used for the data analysed, in which radiances were sorted into geographic groups based on latitude before invoking the appropriate regression coefficients. Secondly, because the satellite and radiosonde data were collected during different periods, biases could reflect variations in the climate between the two periods or between data for a single year and a ten-year average.

For climatic model construction, the models based on satellite retrievals (to be used at maritime locations lacking radiosonde stations) should closely match those based on radiosonde retrievals (to be used where available). Failure to match would produce discontinuities in the model parameters between the region using radiosonde data and that using satellite data.

The model parameters derived from radiosonde soundings were adopted as the calibration standard for consistency with the method used by the Australian Bureau of Meteorology for mixing-ratio retrievals from satellite data, which is described by Kelly et al. (1983). The latter involves a linear transformation of satellite radiance measurements to achieve agreement with coincident radiosonde profiles.

In the present study, parameters derived from the single year of satellite retrievals were calibrated to agree with the average of ten years of radiosonde measurements at the matched sites. This procedure corrected for biases arising from both retrieval technique and climate change. The correction equation obtained from these matched sites was then applied at all unmatched satellite sites to bring their parameters into better alignment with what might have been obtained had they been based on ten years of radiosonde retrievals at these sites.

Rather than use the model coefficients β_j and δ_j directly, the amplitudes

$$\beta_{12} = (\beta_1{}^2 + \beta_2{}^2)^{1/2},$$
$$\beta_{34} = (\beta_3{}^2 + \beta_4{}^2)^{1/2},$$
$$\delta_{12} = (\delta_1{}^2 + \delta_2{}^2)^{1/2},$$

were employed to achieve a calibration between

$\beta_0{}^R(p)$ and $\beta_0'(p)$
$\beta_{12}{}^R(p)$ and $\beta_{12}'(p)$
$\beta_{34}{}^R(p)$ and $\beta_{34}'(p)$
$\delta_{12}{}^R(p)$ and $\delta_{12}'(p)$

for p = surface, 850 hPa, 700 hPa, 500 hPa, 400 hPa. Initially, phase angles were not calibrated because the pilot assessment suggested this was not necessary. However, phase calibration between radiosonde and satellite was eventually needed in some cases.

The equation used in each case was of the form

$$\theta^R - \theta' = B_0 + B_1\,\lambda, \qquad \ldots 12$$

where θ represents any of the $\beta_0(p)$, ... and λ is again the latitude measured in degrees south of the equator. The coefficients B_0 and B_1 were estimated for each model parameter and at each pressure height using linear regression on data from the 19 maritime matched satellite/radiosonde sites. The results showed that most coefficients in Eqn 12 are significant for most θs at the higher levels but only the semi-annual component

Fig. 2 **Dependence of satellite to radiosonde calibration on latitude for average mixing ratio β_0 at 700 hPa pressure height.**

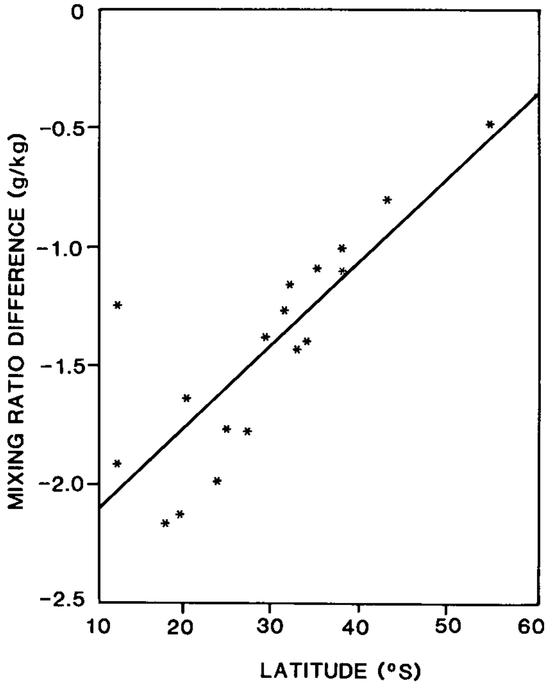


Table 1. Comparison of final satellite and radiosonde parameters for 19 matched maritime locations. Standard deviations of error between satellite and radiosonde parameters.

	Pressure (hPa)								
	1000			*700*			*400*		
Parameter	$\Delta\theta$ *dg kg*$^{-1}$	$\Delta\theta/\bar{\beta}_0$ *%*	$\Delta\theta/\bar{\delta}_0$ *%*	$\Delta\theta$ *dg kg*$^{-1}$	$\Delta\theta/\bar{\beta}_0$ *%*	$\Delta\theta/\bar{\delta}_0$ *%*	$\Delta\theta$ *dg kg*$^{-1}$	$\Delta\theta/\bar{\beta}_0$ *%*	$\Delta\theta/\bar{\delta}_0$ *%*
B_0	10.8	11	56	2.8	9	17	0.4	7	8
B_{12}	13.7	14	71	2.2	7	13	0.7	12	14
B_{34}	3.7	4	19	1.5	5	9	0.3	6	7
δ_0	3.8	4	20	3.2	10	19	0.8	14	16
δ_{12}	4.8	5	25	1.8	4	8	0.4	7	8
$\bar{\beta}_0$		95.3			30.6			5.9	
$\bar{\delta}_0$		19.4			16.7			5.1	

is significant at the surface level. The dependence of the correction on latitude is illustrated in Fig. 2 for the case of β_0 at the 700 hPa pressure height, when both parameters yielded a significant t-value.

In all cases, the estimated values of B_0 and B_1 were used to calculate the final satellite values from the equation

$$\theta^s = \theta' + B_0 + B_1 \lambda. \qquad \ldots 13$$

A comparison of the final satellite parameters θ^s with the radiosonde parameters θ^R was made by evaluating the standard deviation of the residuals for the fitted calibrations in Eqn 12 for the parameters β_0, β_{12}, β_{34}, δ_0, δ_{12} at the 19 matched maritime stations. This is equivalent to calculating the root mean squared error between the radiosonde and final satellite values. These standard deviations were also compared with the average mixing-ratio mean $\bar{\beta}_0$ and standard deviation $\bar{\delta}_0$ for these stations. The results, presented in Table 1, indicate that some unacceptably large discrepancies between satellite and radiosonde data remain, namely $\Delta\beta_0 \ / \ \bar{\delta}_0 = 56\%$ and $\Delta\beta_{12}/\bar{\delta}_0 = 71\%$ at 1000 hPa. For the other parameters and for these parameters at greater heights the agreement is acceptable.

Discussion

The climatic model described in this paper, which estimates the expected atmospheric moisture at a given location, date and time, achieves a very substantial reduction in the volume of data required. For radiosonde data, the initial 3650 measurements (daily for ten years) at each pressure height and each radiosonde station are reduced to the eight parameters $\beta_0, \ldots, \beta_4$ and $\delta_0, \ldots, \delta_2$. This is a data reduction of almost 460:1. For satellite data only one year was analysed, thereby reducing 365 measurements to eight and achieving a data reduction of 46:1.

The success of this climatic model is judged by the precision with which it predicts atmospheric moisture. A suitable measure of prediction precision is the ratio of the constant term for standard deviation to the constant for the mean, namely δ_0/β_0. A box plot (see Paper A and Velleman and Hoaglin 1981) of this ratio expressed as a percentage is given in Fig. 3 for radiosonde data at five of the available eight pressure heights. At 1000 hPa δ_0/β_0 is generally less than about 30 per cent but, as altitude increases, the predictive usefulness of the climatic model for mean mixing ratio degrades until δ_0/β_0 ratios approach 100 per cent and 400 hPa. Of course, at these higher altitudes, mixing ratio values are generally small and the component of error standard deviation due to measurement by radiosonde equipment may be more dominant at higher levels. For satellite soundings at the 34 locations not matched to radiosonde sites, similar box plots are given in Fig. 4. A similar pattern emerges as that in Fig. 3 with a tendency for the satellite models to indicate slightly more variability due, perhaps, to the combined effects of using only a one-year sample and to the possibility that satellite retrievals contain larger measurement variability than radiosonde retrievals.

The bias between the satellite retrievals and radiosonde measurements was unexpected, since the Bureau of Meteorology obtained the former using regression analysis to achieve agreement with the latter. Examination of the geographical distribution of the biases suggested that inland areas behaved differently from coastal areas and that the bias depended on latitude. A regression model incorporating both latitutde and a binary coastal/inland indicator variable confirmed the importance of both parameters. Since the satellite data was needed only over the oceans, the bias analysis was restricted to coastal data, for which the single parameter of latitude was sufficient.

Even after correction for bias, the satellite model has two distinct defects compared with the

Fig. 3 Box plots of ratio of constant term for standard deviation to constant for mean — 31 radiosonde stations.

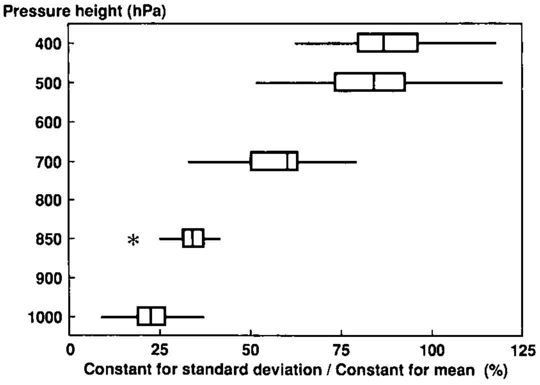
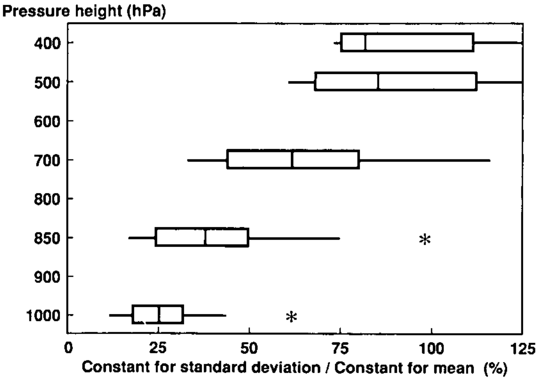


Fig. 4 Box plots of ratio of constant term for standard deviation to constant for mean — 34 unmatched satellite locations.



radiosonde model. First, data are available for only five of the eight pressure heights at which radiosonde data are available. This limitation is intrinsic to the satellite retrieval technique and is therefore unavoidable. Second, residual errors (after correction for bias) between the satellite and radiosonde parameters for the 19 matched maritime locations are unacceptably large in some cases. These errors would probably be reduced by analysing several years of satellite data rather than the single year considered here.

Since November 1987, the Australian Bureau of Meteorology has used a physically based system described by Le Marshall et al. (1989) for deriving atmospheric temperature and moisture soundings from TOVS data, rather than the statistically based method used to obtain the data analysed in this paper. The advantages of the physically based scheme include explicit treatment of surface parameters (such as skin temperature, emissivity and elevation), the computation of cloud height and amount in the processing scheme, and proper treatment of non-nadir radiances to avoid the problems often inherent in statistical limb correction. This more recent operational system may well have overcome the bias problems identified in the present study of data obtained with an earlier scheme.

Conclusion

The annual variation of atmospheric moisture in the Australian region has been modelled at eight pressure heights from radiosonde measurements at 31 locations and at five pressure heights from satellite retrievals at an additional 34 unmatched locations. The diurnal cycle and the annual change in the diurnal cycle of atmospheric moisture have also been modelled, using different methods for radiosonde and satellite data. At the radiosonde stations, the diurnal and interaction parameters were modelled directly from three-hourly surface recordings. At the 34 unmatched satellite locations, the diurnal and interaction parameters were predicted by a linear function of the constant and annual terms plus latitude.

The standard deviations of these estimates of atmospheric moisture were also modelled from the same data in a similar manner. The results indicate that for the radiosonde model the moisture is estimated to an accuracy generally better than 30 per cent of the mean value close to the surface but degrading to about 100 per cent of the mean value at a pressure height of 400 hPa. Consequently, the climatic model has a useful prediction capability close to the surface but its usefulness decreases with increasing altitude.

In the model derived from satellite data, however, although the moisture is estimated to an accuracy of 20 to 30 per cent, a bias from the radiosonde model of a similar magnitude makes the errors unacceptably large. The precision of the satellite model could probably be improved to an acceptable level by analysing data over a longer period of time.

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