CHAPTER 1

WATER VAPOUR IN THE ATMOSPHERE – A BRIEF REVIEW

1.1 Introduction

Water vapour, although it constitutes less than 3 percent by volume of the atmosphere, even at sea level with moiet conditions, is the most important variable gas in the atmosphere. It abeorbs nearly six times as much solar radiant energy as all the other gases combined and accounts for nearly all of the gaseous absorption of terrestrial radiation. With the liquid water and ice particles suspended in the atmosphere, water vapour plays a predominant role not only in the radiation balance but in the whole mechanism of heat transfer in the atmosphere.

Equally important are the thermodynamic effects of water vapour in its role of dew, froet, cloud, fog and precipitation formation, which are responsible for what we all call weather. The measurement of the water vapour content of the atmosphere and an understanding of its thermodynamic effects is therefore of vital concern to meterologists and hydrologists. It plays a crucial role in the dynamics of the atmosphere, because it is a source of atmospheric energy and its presence affects the release and transformation of both elec-

trical and thermal energy, being the origin of all hydrometeors and the main absorber in the lower atmosphere of infra-red radiation. In addition, the water vapour content .of the air can be used as a natural tracer, both horizontally and vertically, in meteorological studies.

In the infrared and far infrared, water vapour is a selective absorber, absorbing almost totally at wavelengths greater than 27μ and between 5.5 and 7μ . It has also a few narrow absorption bands below 4μ and absorbs moderately from 4 to 5.5 μ , 7 to 8 μ and 13 to $27 P$. However, for wavelengths from 8 to 13μ , it is almost perfectly transparent. Recent precise determinations of water vapour absorption in most regions of the solar and terrestrial radiation spectra (Fig 1.1) have given a fairly complete picture of the absorption by water vapour in the various regions of the solar spectrum (Valley, 1965).

Water vapour in the atmosphere varies widely with time and locality and with height in the atmosphere. Though most of the water vapour is confined to the lower troposphere, measurable amounts have also been detected in the stratosphere up to 30 km.
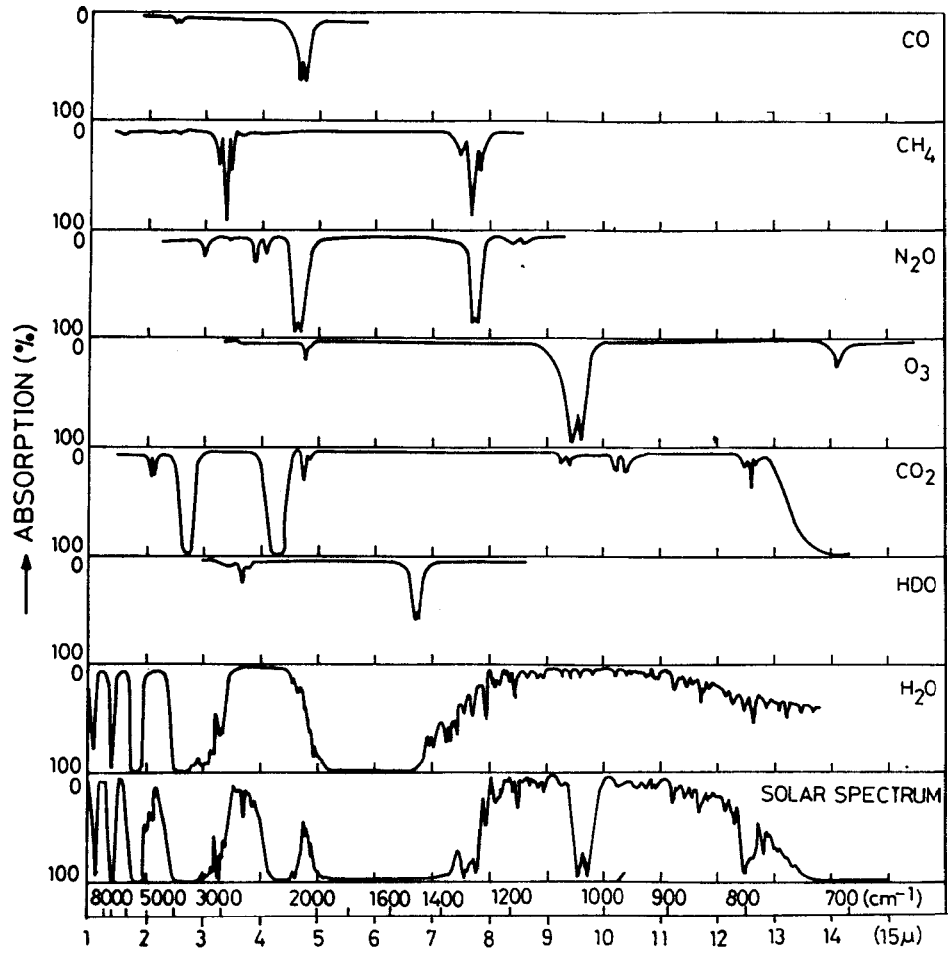
The maximum amount of water vapour which the

Fig 1.1 Water vapour absorption in the various regions of solar and terrestrial radiation spectra.

atmosphere can contain is regulated by its tempera-
ture. For **example,** at the highest recorded station
temperature of about $55^{\circ}C$, the air can **hold** about
100 g m^w . The amount **actually** present in the atmos-
phere is a **complex** function of various weather para-
meters. The highest water **vapour** content   recorded
is about 30 g m^{-3}, corresponding to a dew point of
approximately $30^{\circ}C$. As the temperature decreases,
the amount of water vapour the air contains decreases
rapidly, approaching a **negligible** amount at tempera-
tures **below** $-40^{\circ}C$ to $-50^{\circ}C$. At these **low** temperatures,
the amount of water vapour the air can contain at the
surface is 10^{-1} and 4 x 10^{-2} g m^{-3}, **respectively.**
Although the water vapour content at temperatures
below $-40^{\circ}C$ is **extremely small,** even this amount is
important in the transmiasion of infrared **radiation**
over **long** path **lengths** (**Wolfe,** 1965).

1.2   **Terminology and Units of Measurement**

1.2.1   **Fundamentally, all** measurements of water vapour
or atmospheric humidity are based on quantities **related**
to evaporation and condensation over a **flat** surface of
pure water. From a water surface that is evaporating,
the excess of **molecules** of water **leaving** the surface,

over those coming back, is expressed and measured as
a pressure. This pressure depends only on the tem-
perature of the water surface. If the quantity of
water vapour present does not vary by either addition
by evaporation or removal by condensation, the vapour
pressure will remain constant, provided the total
pressure of all the gases does not change.

1.2.2   The ways in which water **vapour** in the atmos-
phere can be specified are many and varied. The
terminology used in **this** study follows the official
definitions and specifications of the parameters of
water vapour laid down by the World Meteorological
Organization (1971). The units normally used for
expressing the various quantities associated with
water vapour in the atmosphere are:

(i) Vapour presaure, in millibars,

(ii) Deneity of water vapour or absolute
humidity, in g/cm^3 or g/m^3,

(iii) Moisture content or specific humidity,
in g/kg,

(iv) Mixing ratio, in g/kg, and

(v) Relative humidity, in per cent.

The terms and units used are described in detail
below.

1.2.2.1   **Vapour** pressure, e, of water vapour in moist
air at total **pressure** p and with mixing ratio r, **is**
defined by $e = \dfrac{r}{0.622 + r} \cdot p$ and is an absolute
measure of the quantity of water vapour present.

1.2.2.2   saturation **vapour** pressure, e_w, of pure aqueous
water vapour with respect to water, is defined as the
pressure of the vapour when in a state of neutral equi-
librium with a plane surface of pure water at the same
temperature and pressure.   Similarly e_i is saturation
vapour pressure over ice.   Both vary with temperature
so that the higher the temperature, the greater the
vapour pressure required for saturation.   It is again
expressed **in** millibars.

1.2.2.3 Relative humidity, U_w, with respect to water,
of moist air at pressure p and temperature T, is the
ratio in per cent of the two vapour **pressures,** the
actual and the **saturation** vapour pressure.   The actual
vapour pressure changes with atmospheric pressure and
the saturation vapour pressure with temperature.

It is expressed as:

$$U_W = 100 \left(\frac{e}{e_W}\right) \qquad (1.1)$$

1.2.2.4 <u>Density or concentration of water vapour or absolute humidity</u>, d_V, is the amount of moisture contained in a unit volume and is usually expressed in g/cm^3 or g/m^3. It is defined as the ratio of the mass vapour m_V to the volume V occupied by the mixture:

$$d_V = \frac{m_V}{V} \qquad (1.2)$$

1.2.2.5 <u>Moisture content or masa concentration or specific humidity</u>, q, of moist air, is defined as the ratio of the mass m_V of water vapour to the mass $(m_V + m_a)$ of moist air, in which the masa of water vapour m_V is contained:

$$q = \frac{m_V}{m_V + m_a} \qquad (1.3)$$

Now $m_V = d_V.V$ and $m_a = d_a.V$,

As the V's cancel, we have

$$q = \frac{d_V}{d_a + d_V} \qquad (1.4)$$

the denominator being the total density of the dry
air, d_a, plus that of the water vapour d_v.

1.2.2.6   The **mixing** ratio, r, is defined as the ratio
of the mass m_v of water vapour to the mass m_a of
dry air, with which the water vapour is associated.

$$r = \frac{m_v}{m_a} \qquad (1.5)$$

It differs from specific humidity only in that it
is related to dry air instead of the total of dry
air plus water vapour.

1.2.2.7   The dew and frost point temperature, T_d and
T_f, of moist air at pressure p and mixing ratio r,
are the temperatures at which moist air, saturated
with respect to water or **ice** at the given pressure,
has a saturation mixing ratio r_w equal to the given
mixing ratio r.   In saturated conditions, the dew point/
frost point and air temperatures are equal.

1.2.2.8   Gaa eauation for water **vapour**

As long as no oondensation or fusion is
taking place, water vapour may be treated as an ideal
gas. For an ideal gas, the following relation exists

between pressure p, density ρ and absolute temperature T.

$$p = \frac{R^*}{m} \cdot \rho \cdot T. \tag{1.6}$$

where R^* is the universal gas constant and **equals 83.12 x 10^6 ergs/gm** degree or **1.986 cal/gm** degree and m is the molecular weight of gas. If e is the water vapour pressure **and** M_w is the molecular weight of water **(18)**, d_v its density and T its temperature and M_a the molecular weight of dry air **= 28.9**,

$$d_v = \frac{e}{R^*T} \cdot M_w = \frac{M_w}{M_a} \cdot \frac{e}{RT} \tag{1.7}$$

where $M_w/M_a = 0.622$ **and** $R = R^*/M_a$ **is** the gas constant for dry air,

$$d_v = 0.622 \cdot \frac{e}{RT} \tag{1.8}$$

The total density of the moist air ρ is the sum of the density of dry air and of water vapour.

The partial pressure of dry air is p–e, where p is the total pressure of moist air. Consequently

$$\rho = \frac{p-e}{RT} + 0.622 \frac{e}{RT}$$

$$\rho = \frac{p}{RT} \left(1 - 0.378 \frac{e}{p} \right) \tag{1.9}$$

This equation shows that moist air is lighter than
dry air at the same temperature and pressure,
for water vapour is lighter than the air it replaces.

According to equation (1.4) moisture content or
specific **humidit**

$$q = \overline{} \over d_a + d_v$$

Expressing it in terms of easily measurable quantities,
we have, substituting for d_v and d_a

$$q = \frac{0.622e}{p-0.378e} \quad g/g \tag{1.10}$$

For ordinary values of the vapour pressure, q can be

expressed as $q = \dfrac{0.622e}{P}$ g/g $\qquad$ (1.11)

without appreciable error.

The specific humidity at **saturation** pressure q_s is

written as $q_s = \dfrac{0.622e_s}{p-0.378e_s}$ $\qquad$ (1.12)

1.3 <u>Techniques of measurement of water **vapour** in
     the atmosphere</u>

Unlike atmospheric pressure and temperature,
measurement of humidity is one of the least satis-
factory of instrumental procedures in meteorology
and it is a field in which great opportunities still
exist for research and invention, particularly for

measurements at very low temperatures and at very
low humidities.

Routine measurements of water **vapour** at meteoro-
logical observatories are made with psychrometers,
hair hygrographs or electrical capacitance and conduc-
tivity sensors to obtain surface humidities; and frost
point hygrometers, infrared absorption spectrometers
or electric hygrometers, using aircraft and balloons
as observing platforms, to obtain **humidities** in the
upper atmosphere.

The methods for measurement of air humidity fall
into six main classes:

    i) Psychrometry
    ii) Dew point hygrometry
   iii) Electric hygrometry
    iv) Spectroscopic hygrometry
     v) **Coulometric** hygrometry, and
    vi) Methods using the change in dimensions,
        weight **etc.** of organic hygroscopic sub-
        stances such as human air, gold beater[1]s
        skin etc.

A number of other sensors such as thermal conductivity
cells, piezoelectric sorption hygrometere, liquid
film hygrometers, capacitive humidity sensors and
self-heating **phase** transition **hygrometers,** (the most

common being **lithium** chloride heated electrical hygro-
meters or dewcells) have also been developed and some
are in regular use. Other recent developments of interest
related to humidity transducers using **aluminium oxide,**
barium fluoride and piezoelctric crystals.

Reliable measurements of water vapour up to about
15 km have been made from aircraft using absorption
hygrometers employing the $6.3\,\mu$ absorption band of water
vapour. The dew or frost point hygrometer has been
found **satisfactory** to greater heights and low tempera-
tures. It has also the great practical advantage that
it needs only a very simple calibration (**Dobson** and
Brewer, 1951).

The measurements which have so far been made in the
atmosphere show that wide variations of relative humi-
dity occur in the atmosphere and any relative humidity
between 30 and 90 per cent is common, with large diurnal
variations at the ground. Relative humidities of about
5 per cent are relatively infrequent and the lowest which
has yet been observed is 0.65 per cent at $266^{\circ}K$ and a
frost-point temperature of $219^{\circ}K.$ The stratosphere **is**
found to be extremely dry with relative humdities of the
order of 2 to 3 per cent over ice. The commonly observed

existence of **cirrus** layers at the tropical **tropopause** level
point to substantially saturated air at and imme-
diately below the tropopause.

In the tropopause, the water vapour distribution
is extraordinarily **complex.** The atmosphere can be
very moist, very dry or very variable with intense
stratification. The structure of the water vapour
distribution presumably arises from the complex
dynamic movements which occur in the atmosphere and
these are too poorly understood at present to permit
a clear explanation of any particular observed distri-
bution.

1.4 <u>Precipitable water in the atmosphere and its measurement</u>

1.4.1 <u>Definition</u>

If we consider an air column of **cross-sectional**
area of 1 cm^2**,** the total mass of water vapour W
contained between the height O and the height **z**
would be:

$$W = \int_{0}^{z} d_v . dz \qquad (1.13)$$

where d_v is the vapour density or absolute humidity.
Substituting for the hydrostatic equation $dp = - \rho g . dz$

where $\rho = d_v + d_a$ is the total air density, we have:

$$W = \int_p^{p_0} \frac{d_v}{\rho} \cdot \frac{1}{g} \cdot dp$$

$$= \frac{1}{g} \int_p^{p_0} q \cdot dp \qquad (1.14)$$

where q is the **specific** humidity defined as $\frac{m_v}{m_v + m_a}$
This can be integrated in stepe or by making a plot
of the specific humidity against **pressure and finding**
the area between the plotted curve **and** q = 0 **and** the
lines p and p_0.

It is, however, simpler to exprees the quantity
in terms of **vapour pressure** and pressure. Since
q = 0,622 e/p approximately, vide equation (1.11)

$$W = \frac{0.622}{g} \int_p^{p_0} e \frac{dp}{p}$$

$$W = \frac{0.622}{g} \int_p^{p_0} e \cdot d(\ln p) \qquad (1.15)$$

W is the precipitable water in **grammes** per square **centimetre** of area. The last integral can be obtained graphically or integrated using a computer. It is commonly reported **as** the height at which the liquid would stand if it were completely condensed in a vessel of the same unit cross-section as the air column. Since the density of liquid water is 1, a height of 1 cm corresponds to 1 **gm.cm^{-2} precipi-** table water.

1.4.2   Measurement of **precipitable** water

A number of techniques have been developed during the last few decades, for the measurement of computation of precipitable water in the atmosphere.

The most commonly used method of measurement is that using the selective absorption of infrared radiation by water vapour. The instrument is either located at the ground using the sun as the source or on satellites, when the upwelling radiation from the earth is used **as** the source. In both cases, measurements are made of the intensity of infrared radiation in two adjacent regions of the spectrum, one in a water vapour absorption region and the other, where no water vapour absorption occurs. The ratio of the intensities enable the precipitable water in the path

of the radiation to be calculated. A second method is
the use of selective absorption in the microwave
region of the spectrum. In the present study, both
these methods were used. The infrared spectral hygro-
meter and microwave radiometer designed and constructed
by the author, their principles of construction and
operation, their calibration and measurement, the
accuracy and sources of error and the results obtained
are described in detail in Chapters 3 and 4.

1.4.3 Computation of **precipitable** water

The most simple and direct method for the compu-
tation of precipitable water in the atmosphere is by
integration from radiosonde measurements of absolute
humidity in the atmosphere. A second method earlier
used and later abandoned is the estimation of total
precipitable water using an empirical relationship
between surface water vapour pressure values and the
precipitable water in the atmosphere. The radiosonde
method was used in the present study to calibrate the
infrared spectral hygrometer and microwave radiometer
observations. Both methods of computation are **described**
in Chapter 2 and their'advantages-and **disadvantages reviewed.**

1.5 Purpose of the studs

The original motivation for undertaking the present

study was the evaluation of two sites as locations
suitable for a millimetre wave radioastronomical
telescope. The most important factor determining the
suitability of a site for ground-based observations
in the millimetre wavelength range 300μ to 3mm, is
the attenuation by absorption and scattering of the
radiation caused by more or less constant components
of dry air, and the variable amounts of precipitable
water in the atmosphere. The amount of excess atte-
nuation and refraction depends on the distribution
of water vapour along the path of propagation, and
for the stratified atmosphere and for the skew rays
the most reliable correlator for evaluation and pre-
dictions of the propagation properties seems to be
the amount of water vapour measured at the observa-
tion site. Statistics of the amount and variation
of zenithal W are therefore of importance for
infrared and short wavelength radio astronomy,
satellite communication and long range propagation
studies in general.

The two sites provisionally chosen for the loca-
tion of the radioastronomical telescope were Bangalore
(Lat. 12° 58'N, Long. 77° 35'E 950 metres a.m.s. l)
and Nandi Hills (Lat. 13° 22'N Long. 77° 41'E,
1479 metres a.m.s. l). Bangalore is centrally located

on the Mysore plateau, about 300 km from the sea both
to the east and the west, Nandi Hills, being a small
hill station about 56 km north of Bangalore. Both
have a ealubrioua and equable climate, Nandi Hills
being naturally cooler and drier due to its higher
elevation.

The four months from December to March are gen-
erally dry. April and May are characteriaed by
thunderstorm activity, mostly in the afternoons and
evenings. The remaining six months experience clou-
diness and rain, as a result of the south-west monsoon
from June to September and the north-east monsoon
during October and November.

The present thesis describes the infrared spectral
hygrometer and microwave water vapour radiometer designed
and constructed by the author for the measurement of
precipitable water in the atmosphere. The results of
these measurements and the computation of precipitable
water from radiosonde data are presented at two stations
over a period of four years, providing the first detailed
study of the kind for these latitudes. The relative
advantages and disadvantages of each method based on
long-term intercomparisons between different instru-

ments and techniques are also assessed. The results,
apart from being of interest to radioastronomers,
meteorologists and communication engineers dealing with
microwave propagation of the atnosphere, provide inval-
uable ground truth measurements for verification of
satellite derived data on precipitable water.

LIST OF SYMBOLS USED

d_a — density of dry air

d_v — absolute humidity or water vapour density

e — vapour pressure of water vapour

— saturation vapour pressure over water

e_i — saturation vapour pressure over ice

m_a — mass of dry air

m_v — mass of water vapour

P — atmospheric pressure

q — moisture content or specific humidity

r — water vapour mixing ratio

r_w — saturation mixing ratio at the pressure and temperature of the moist air

R^* — universal gas content

T — temperature

T_d — thermodynamic dew point temperature

T_f — thermodynamic frost point temperature

V — volume occupied by mixture of water vapour and dry air

u_w — relative humidity with respect to water of moist air

T_w — thermodynamic wet bulb temperature

ρ — density of moist air

<u>LIST OF FIGURES</u>

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