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The Role of Water Vapor in Climate

A Strategic Research Plan for the Proposed GEWEX Water Vapor Project (GVaP)

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Results of a workshop cosponsored by the National Aeronautics and Space Administration and the GEWEX Science Steering Group and held at Tidewater Inn
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Foreword

The concept of a research initiative to improve our knowledge of atmospheric water vapor was formulated during the late 1980s as it became clear that present water vapor measurements were inadequate to define the state of the atmosphere on almost any scale; and furthermore, that GCMs and modern analysis systems lacked the ability to realistically incorporate real moisture data because of the inadequacy of present parameterizations of moist processes and of even the explicit treatment of resolved water vapor transport. Our lack of knowledge concerning atmospheric water vapor is all the more striking considering the dominant impact moisture processes have in the Earth's weather and climate. Clearly, without a good understanding of these processes, we are limited in our ability to quantitatively deal with very fundamental aspects of the earth-atmosphere system such as surface exchanges of moisture and latent heat, horizontal moisture transport and convergence, cloud formation, precipitation, and radiative heating. Our understanding of the role water vapor will play in global warming also suffers from an inadequate knowledge of even total atmospheric moisture content on a long-term global basis, much less of the vertical distribution of moisture.

As a result of these concerns, it was decided that a workshop would be an appropriate mechanism to bring together interested members of the scientific community to discuss the needs and the direction for a research program designed to increase our knowledge of atmospheric water vapor and our understanding of moist processes. A planning meeting for the workshop was held at the NASA/Goddard Space Flight Center (GSFC) during January 1990. At the planning meeting, the overall thrusts and objectives of a new initiative were developed and the need for a workshop was reaffirmed.

The workshop entitled "The Role of Water Vapor in Climate Processes" was held under the auspices of the GEWEX Science Steering Group at Easton, Maryland during the period October 30 through November 1, 1990. A detailed strawman document was prepared by Dr. David Starr, NASA/GSFC, with extensive input from planning meeting attendees and others, and was distributed prior to the workshop.

The workshop was organized into the following three sessions: "Water Vapor Processes in Climate" chaired by Prof. Graeme Stephens of Colorado State University; "Unresolved Problems of Water Vapor in Climate" chaired by Prof. Don Johnson of the University of Wisconsin; and "Water Vapor Observations" chaired by Dr. S. Harvey Melfi of NASA/GSFC. The three chairmen also led discussion/work groups on the same topics during the meeting. As a result of these discussions and papers presented at the workshop, a draft strategic plan was prepared and presented to the GEWEX Science Steering Group of the WCRP Joint Scientific Committee by Dr. Robert Schiffer of NASA/HQ at their January 21-25, 1991 meeting in Bermuda. Detailed comments on the draft plan were solicited from the workshop attendees and incorporated into the present plan.

The GEWEX Science Steering Group has endorsed key elements of this plan for the proposed GVaP as components of a pilot study designed to determine the feasibility of producing a long term water vapor climatology for WCRP and GEWEX. These elements are the a) intercomparison of water vapor measurements from balloons with measurements using active and passive remote sensing techniques; b) establishment of one or two ground-based reference stations (e.g., Raman lidar) for long term observation of temporal variations; and c) compilation of an experimental global water vapor data set based upon existing satellite obsevations. It is anticipated that the first phase of the implementation plan for the proposed GVaP will encompass the elements of the pilot study.

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D. O'C. Starr
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List of Acronyms

AIRS	Atmospheric Infrared Sounder
AMSU	Advanced Microwave Sounding Unit
ASOS	Automated Surface Observing System
ASTEX	Atlantic Stratocumulus Transition Experiment
CLASS	Cross-chain Loran Atmospheric Sounding System
COARE	Coupled Ocean-Atmosphere Response Experiment
DIAL	differential absorption lidar
DMSP	U.S. Defense Meteorological Satellite Program
DOE	U.S. Department of Energy
ECMWF	European Centre for Medium Range Weather Forecasting
ENSO	El Niño - Southern Oscillation
EOS	Earth Observing System
ERBS	Earth Radiation Budget Satellite
FDDA	four-dimensional data assimilation
FIRE	First ISCCP Regional Experiment
GCM	general circulation model
GEWEX	Global Energy and Water Cycle Experiment
GOES	Geostationary Operational Environmental Satellite
GPCP	Global Precipitation Climatology Project
GVaP	GEWEX Water Vapor Project
HAPEX	Hydrological-Atmospheric Pilot Experiment
HIRS	High-resolution Infrared Sounder
HIS	High spectral resolution Interferometer Sounder
IGPO	International GEWEX Project Office
ISCCP	International Satellite Cloud Climatology Project
ISLSCP	International Satellite Land Surface Climatology Project
LASE	Lidar Atmospheric Sensing Experiment
LAWS	Lidar Atmospheric Wind Sounder
MOBILHY	Modélisation du Bilan Hydrique
MODIS	Moderate-resolution Imaging Spectrometer
MSU	Microwave Sounding Unit
NASA	U.S. National Aeronautics and Space Administration
NCAR	U.S. National Center for Atmospheric Research
NMC	U.S. National Meteorological Center
NOAA	U.S. National Oceanographic and Atmospheric Administration
NRC	U.S. National Research Council
NWS	U.S. National Weather Service
PW	precipitable water vapor
SAGE	Stratospheric Aerosol and Gas Experiment
SPECTRE	Spectral Radiance Experiment
SMMR	Scanning Multifrequency Microwave Radiometer
SSM/I	Special Sensor Microwave/Imager
SST	sea surface temperature
STORM	Storm-scale Operational and Research Meteorology Program
TOGA	Research Programme on Interannual Variability of the Tropical Ocean and Global Atmosphere
TOVS	TIROS Operational Vertical Sounder
TRMM	Tropical Rainfall Measuring Mission
VAS	VISSR Atmospheric Sounder
VISSR	Visible Spin-Scan Radiometer
WCRP	World Climate Research Program
WOCE	World Ocean Circulation Experiment

The Role of Water Vapor in Climate:
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Executive Summary

The proposed GEWEX Water Vapor Project (GVaP) addresses fundamental deficiencies in the present understanding of moist atmospheric processes and the role of water vapor in the global hydrologic cycle and climate. Inadequate knowledge of the distribution of atmospheric water vapor and its transport is a major impediment to progress in achieving a fuller understanding of various hydrologic processes and a capability for reliable assessment of potential climatic change on global and regional scales. GVaP will promote significant improvements in knowledge of atmospheric water vapor and moist processes as well as in present capabilities to model these processes on global and regional scales. GVaP complements a number of ongoing and planned programs focused on various aspects of the hydrologic cycle including: HAPEX and ISLSCP and their various field campaigns for surface fluxes over land, WOCE and TOGA/COARE for air-sea interaction, ISCCP and FIRE for clouds and cloud formation, and GPCP, STORM and TRMM for precipitation.

The goal of GVaP is *to improve understanding of the role of water vapor in meteorological, hydrological, and climatological processes through improved knowledge of water vapor and its variability on all scales.* This goal is motivated by the importance of atmospheric water vapor in three fundamental respects:

1) Water is a principal medium for direct energy exchange among the major components of the Earth System--atmosphere, hydrosphere, cryosphere, biosphere and lithosphere--and by virtue of its mobility, provides for relatively rapid interaction. Knowledge of the distribution of atmospheric water vapor and its horizontal and vertical transport is essential for achieving a full understanding of hydrologic processes which strongly couple these systems and regulate climate. Although efforts are underway to improve knowledge of global cloudiness (ISCCP) and precipitation (GPCP), an adequate description of the associated global distribution of even total column water vapor is not presently available.

2) Water vapor is *the* predominant greenhouse gas and plays a crucial radiative role in the global climate system. Most climate models show a significant increase in atmospheric water vapor in response to climate warming associated with increased concentrations of other greenhouse gases, such as CO_2, or with other causes, such as solar variability. In most models, the consequent radiative effects of changes in atmospheric water vapor concentration strongly amplify the climatic response leading to further warming. Regardless of our capability to accurately compute radiative fluxes, inadequate knowledge of atmospheric water vapor, particularly in the upper troposphere, will necessarily compromise confidence in those computations and in our ability to define the climate system.

3) Water vapor is an essential ingredient in many atmospheric processes which are intimately involved in determining specific realizations of climate variations, especially on regional scales. Our present inability to properly simulate many important details of the present climate is largely associated with our poor understanding of moist processes such as surface evaporation, cloud formation and precipitation, and their interaction with the circulation of the atmosphere. Improvements in parameterizations of moist processes for use in global climate models depends on an adequate understanding of the processes themselves which are characteristically organized at the mesoscale. Highly detailed descriptions will be required to resolve these fundamental physical processes.

Four central scientific objectives of GVaP have been identified. They are:

1) *To develop and apply algorithms to obtain an accurate global climatology of the horizontal and vertical distribution of atmospheric water vapor.* The value of even a relatively gross description of atmospheric water vapor for use in validating and improving climate models is extremely high at this time. It is recommended that a coordinated effort be made to derive a monthly climatology of the global distribution of vertically integrated water vapor (precipitable water vapor, PW) using a combination of satellite and conventional observations. Further, it is recommended that the feasibility of constructing a coarse vertical resolution, global, water vapor data set be examined.

2) *To develop and improve techniques to provide high vertical resolution global measurements of water vapor from satellites.* To adequately analyze global and regional climate and hydrologic systems, data assimilation models will need to employ a vertical resolution compatible with the inherent vertical scales of atmospheric moisture structure and will require global observations on a comparable vertical scale. Although significant improvements in present capabilities are anticipated over the next decade, it is unlikely that passive remote sensing techniques will ever achieve the required vertical resolution. Thus, it is recommended that a concentrated effort be made to advance the technology of active lidar-based systems, which have the potential for achieving the desired vertical resolution from space platforms and which would strongly complement the high horizontal resolution achieved by passive systems.

3) *To improve knowledge of water vapor and its variability in relation to key hydrological processes by establishing a long-term climatology of the vertical distribution of atmospheric water vapor at selected sites and by conducting regional field campaigns in diverse climatological regimes.* The latter would be conducted in conjunction with ongoing or planned intensive field experiments focused on various important hydrologic processes and would involve increased emphasis on water vapor observations and analysis as part of a comprehensive effort to observe and model the subject physical processes. The longer duration (at least seasonal) high-resolution observations from selected surface-based remote sensing sites at climatically sensitive locations and times would serve to dramatically advance our basic knowledge of atmospheric water vapor structure, variability and transport. In addition to water vapor in the lower troposphere, a strong focus on middle and upper tropospheric water vapor is also required.

4) *To promote basic research contributing to an improved understanding of the role of atmospheric water vapor and its variability in meteorology, hydrology, and climatology.* High-priority research activities include: analysis of water vapor observations on all scales in relationship to pertinent meteorological or other parameters to improve basic knowledge; detailed modeling studies to improve basic understanding of various hydrologic processes; data assimilation experiments to quantify the sensitivity of analyses to improvements in the assimilation of water vapor observations and the parameterization of hydrologic processes; and GCM experiments designed to improve understanding of the global hydrologic cycle and climate system and to quantify model sensitivity to improvements in parameterizations of hydrologic processes.

In order to achieve these objectives, present capabilities for obtaining high-quality water vapor observations must be significantly improved. The existing upper air sounding network must be improved and standardized so that it provides consistent, high-quality water vapor profiles. Research and development to advance water vapor measurement technology using remote sensing or *in-situ* methods from surface, aircraft and spacecraft platforms must also be strongly promoted. In particular, capabilities for making water vapor observations in the upper and middle troposphere must be dramatically improved. *It is essential that a full quantitative characterization be made of all present and developmental water vapor sensing systems.* This will require coordinated intercomparison activities over a range of environmental conditions and establishment of absolute standards. Moreover, there must also be a very strong focus on quantitative evaluation of water vapor measurements derived from satellite-based measurements in conjunction with these activities.

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1. Introduction

The important link connecting various aspects of the hydrologic cycle is atmospheric water vapor. Knowledge of the distribution of atmospheric water vapor and its horizontal and vertical transport is crucial to a full understanding of hydrologic processes which play a central role in regulating climate.

A better understanding of the global hydrological cycle, especially the atmospheric component, is needed to assess potential changes in global and regional climate arising from natural variations and from the effects of man's activities. Moist processes play a major role in the climate system by regulating atmospheric circulation and temperature as well as the availability of sunshine and water at the surface. By virtue of its exchange and transport processes, the atmospheric branch of the global hydrologic cycle provides effective coupling among the cryosphere, hydrosphere, biosphere and lithosphere components of the Earth System (e.g., NRC, 1986). Potential changes in the atmospheric hydrologic cycle associated with climate change may have the most important consequences for man given the strong impact of precipitation on the biosphere. Moreover, water vapor and precipitation are expected to be sensitive indicators of climate change (Raval and Ramanathan, 1989).

The importance of water in the climate system cannot be overstated. A large fraction of the energy transferred from the surface to the atmosphere is in the form of latent heat due to evaporation. This heat transfer is a major component of the surface energy budget which determines surface temperature. The subsequent release of this energy in the atmosphere by condensation of water vapor is one of the main sources of energy driving atmospheric circulation and its associated transports (Lorenz, 1967). Water vapor and condensed water in the form of extended cloudiness also strongly modulate the transfer of radiative energy within the atmosphere and thus the overall energy balance of the planet (Ramanathan *et al.*, 1989) as well as atmospheric temperature and circulation.

A major objective of NASA's planned Earth Observing System (EOS) is the description of the global hydrologic cycle. Individual components of the hydrologic cycle are also presently being studied. Major ongoing and planned programs include: the Hydrological-Atmospheric Pilot Experiment (HAPEX) and the International Satellite Land Surface Climatology Project (ISLSCP) for surface fluxes over land; the World Ocean Circulation Experiment (WOCE) and the Research Programme on Interannual Variability of the Tropical Ocean and Global Atmosphere (TOGA) for air-sea interaction; the International Satellite Cloud Climatology Project (ISCCP; Schiffer and Rossow, 1983) and the First ISCCP Regional Experiment (FIRE; Cox *et al.*, 1987) for clouds and cloud formation; and the Global Precipitation Climatology Project (GPCP; WCRP, 1990b), the Storm-scale Operational and Research Meteorology program (STORM; NCAR, 1989) and Tropical Rainfall Measuring Mission (TRMM; Simpson *et al.*, 1988) for precipitation. Knowledge of the distribution of atmospheric water vapor and its horizontal and vertical transport is key to a full understanding of these processes.

A very important aspect of atmospheric water vapor is that it is extremely heterogeneous on all time and space scales. Many important transport processes occur on the mesoscale in association with precipitating cloud systems. It is also important that some crucial hydrologic processes, such as cloud formation and evaporation, are governed by relative humidity. This coupling of moisture concentration and temperature introduces an even greater degree of complexity. Furthermore, the extreme variations of water vapor concentration within the atmosphere present significant measurement difficulties. For example, moisture contents in the cold upper troposphere are typically orders of magnitude smaller than in the warm boundary layer. Water vapor contents near the surface also typically vary by over an order of magnitude between polar and equatorial regions.

Present observations of atmospheric water vapor are largely inadequate for resolving atmospheric hydrologic processes on most important time or space scales. Upper air soundings, which have been the traditional source of water vapor data, have significant shortcomings in accuracy and geographical coverage. Satellite-derived observations of water vapor profiles have neither the accuracy nor sufficient vertical resolution to be generally useful for quantitative applications. Surface-based passive remote sensing is similarly limited with respect to vertical resolution and is of little use in detecting water vapor concentrations in the middle to upper troposphere. *In-situ* measurements aboard aircraft and special purpose balloons are generally more reliable but cannot give a coherent overall picture of moisture distribution. Active remote sensing techniques using lidar have shown great promise but only very limited amounts of data have been obtained. However, significant improvements can be achieved in the areas of passive and active remote sensing of atmospheric water vapor from the surface, from satellites and from aircraft.

1.1 The Global Energy and Water Cycle Experiment (GEWEX)

The Global Energy and Water Cycle Experiment (GEWEX) of the World Climate Research Program (WCRP) has recently been initiated as a major new program for the decade of the 1990s and beyond. This initiative attempts to enhance our rudimentary understanding of the fundamental role of energy and water in determining weather and climate (WCRP, 1988). The broad objectives of GEWEX recognize the essential need to measure the distributions and fluxes of both energy and water over the planet and to understand the intricate interactions operating within weather and climate systems. The objectives of GEWEX are:

1. To determine the hydrological cycle and energy fluxes through global measurements of observable atmospheric and surface properties;

2. To model the global hydrological cycle and its impact on the atmosphere, land surfaces, and oceans;

3. To develop the ability to predict the variations of global and regional hydrological processes and their response to environmental changes; and

4. To foster the development of observing techniques and data management and assimilation systems suitable for operational application to long-range weather forecasts, hydrology and climate predictions.

However, our understanding of the atmospheric branch of the hydrological cycle is meager and unsatisfactory for predicting future climate change. Knowledge of the exchanges of water between the major subsystems of the overall global hydrologic cycle, e.g., ocean-atmosphere, is even less advanced. Some of the most severe difficulties confronting GEWEX arise from measuring, modeling and predicting these interface exchanges including: evaporation/sublimation, evapotranspiration, precipitation and runoff. These difficulties must be addressed. The fluxes of water substance across subsystem boundaries and within the atmosphere are fundamentally important to understanding the hydrologic cycle and climate.

Because of the importance of atmospheric water vapor to understanding of the hydrological cycle and other major energy budgets, a specific focus on water vapor is appropriate within the context of GEWEX.

1.2 GEWEX Water Vapor Project (GVaP)

This document describes a strategic research plan for the proposed GEWEX Water Vapor Project (GVaP). The overall goal of the project is:

> **To improve understanding of the role of water vapor in meteorological, hydrological, and climatological processes through improved knowledge of water vapor and its variability on all scales.**

To meet this overall goal, several important objectives of GVaP have been identified. These are:

1. To develop and apply algorithms to obtain an accurate global climatology of the horizontal and vertical distribution of atmospheric water vapor;

2. To develop and improve techniques to provide high vertical resolution global measurements of water vapor from satellites;

3. To improve knowledge of water vapor and its variability in relation to key hydrological processes by establishing a long-term climatology of the vertical distribution of atmospheric water vapor at selected sites and by conducting regional field campaigns in diverse climatological regimes;

4. To promote basic research contributing to an improved understanding of the role of atmospheric water vapor and its variability in meteorology, hydrology, and climatology.

Section 2 provides a detailed scientific rationale for the goals and scientific objectives of the project. Section 3 reviews the present state of water vapor measurement technology including *in-situ* and remote methods from ground, aircraft, balloon, and satellite platforms. Expectations for improved measurements in the future are also outlined there.

With the first three sections as background, a specific research plan for meeting the GVaP objectives is presented in Section 4. Section 5 gives an overview of other major national and international programs which address aspects of the hydrological cycle. It is expected that GVaP will take advantage of *joint field mission opportunities* afforded by these other programs. Section 6 provides the details for managing both the project and the data which will result. Data management is a key activity if the objectives of GVaP are to be accomplished in a cost-effective and timely manner. Section 7 provides a summary of important recommendations for a successful implementation of this research activity.

2. Science Rationale

2.1 Goal and Motivation

The overall goal of the proposed GEWEX Water Vapor Project (GVaP)--*to improve understanding of the role of water vapor in meteorological, hydrological, and climatological processes through improved knowledge water vapor and its variability on all scales*--is motivated by the critical importance of atmospheric water vapor in three fundamental respects, as described in the following subsections.

1. Water vapor and its associated exchange and transport processes are central to the atmospheric branch of the global hydrologic cycle which provides strong coupling among all the major components of the Earth System.

2. Water vapor is the predominant greenhouse gas and plays a crucial role in regulating the global climate system.

3. Water vapor is an essential ingredient in many atmospheric processes which are intimately involved in determining specific realizations of climate variations, especially on regional scales.

Adequate knowledge of the global distribution and transport of atmospheric water vapor is central to our ability to resolve the global hydrologic cycle and to define the climate system. Improvements in our knowledge of moist processes in the atmosphere and our capability to realistically model these physical processes will require detailed knowledge of the distribution of atmospheric water vapor and other relevant parameters at the appropriate physical scales. Our ability to accurately assess and predict potential changes in global and regional climate will depend on how well we are able to observe and model the flow of water vapor through the atmosphere.

2.1.1 Water Vapor and the Global Hydrologic Cycle

Water plays a fundamental role in an enormous variety of important processes operating within the Earth System. The hydrologic cycle provides one of the most direct paths for interactions among the major components of this global system including the atmosphere, cryosphere, hydrosphere, biosphere and lithosphere (NRC, 1986). *Although the amount of atmospheric water represents only a small portion of the total system water, it is central to the hydrologic cycle and exerts a disproportionate influence on the energy balance of each of the Earth's spheres.* It is a principal medium for energy exchange. In particular, the transfer of water across the earth-atmosphere interface through evaporation, sublimation, evapotranspiration, condensation and precipitation as well as the transport of water within the atmosphere in the form of vapor, cloud droplets and ice crystals represent one of the most rapid and effective coupling mechanisms within the Earth System.

The time scales of the various components of the hydrologic cycle range from minutes to days within the atmosphere to thousands of years within the oceans. A time scale that is fundamental to the hydrologic interaction among the components of the Earth System is the atmospheric cycle time of about 10 days. An amount of water approximately equal to the total global tropospheric reservoir is exchanged across the earth-atmosphere interface every 10 days. This global time scale governs the quasi-horizontal transport of atmospheric water vapor from its source regions--predominantly evaporation over the vast oceans--to its sinks in precipitating weather systems (e.g., Rasmusson, 1967; Peixóto and Oort, 1983). The associated latent heat release within the atmosphere represents a major energy source that directly maintains the atmospheric general circulation and its transports of momentum, energy and water (Lorenz, 1967). In addition, precipitation is a prime determinant of the state of the biosphere. Plentiful precipitation gives rise to tropical rain forests, while meager precipitation is associated with the Earth's great deserts. In turn, water availability and vegetation strongly modulate surface evaporation and evapotranspiration and surface temperatures over land areas.

However, our quantitative knowledge of the atmospheric hydrologic cycle and its variability is primitive. ***Although efforts are underway to improve knowledge of global cloudiness (ISCCP) and precipitation (GPCP), an adequate global description of even the climatological distribution of water vapor is not presently available.*** GVaP seeks to fill this void.

2.1.2. Water Vapor and Global Climate: The Greenhouse Effect

The gains and losses of energy from the atmosphere and the surface by radiative processes are strongly coupled to the hydrologic cycle and are a fundamental determinant of the Earth's climate. Precipitation affects vegetation which acts as a control on the albedo of land surfaces and, thus, on the input of solar energy. Clouds and water vapor also modulate incident solar radiation both in terms of reflecting energy to space and absorbing energy within the atmosphere. The absorption of the surface-emitted infrared radiative energy by clouds and water vapor and, in turn, the re-emission at a lower temperature (the greenhouse effect) substantially moderates the Earth's climate (Manabe and Wetherald, 1967; Stephens and Webster, 1979; Ramanathan *et al.*, 1989).

Because water vapor is the predominant greenhouse gas, it will play a major role in any climate change (Ramanathan, 1988). *Most climate models show very significant increases in atmospheric water vapor in response to climate warming* (Cess *et al.*, 1990). Observed changes in atmospheric water vapor content might therefore serve as a useful indicator of global climate change (Raval and Ramanathan, 1989). Moreover, the increased water vapor content gives rise to a strong positive feedback (increased warming). In simulations of climatic response to a doubling of atmospheric CO_2, for example, models typically show a 70 percent higher surface temperature response due to this feedback in addition to the direct effects of the increased CO_2 (Arking, 1991). Consequently, the importance of other feedback mechanisms, such as clouds and surface albedo, would be much smaller without the underlying and dominant water vapor feedback.

It is also very significant that while the total column water vapor is determined primarily by water vapor in the atmospheric boundary layer (typically about 75 percent of the total), the small amount of water vapor in the middle and upper troposphere may contribute disproportionately to the greenhouse effect. For example, calculations using a simple one-dimensional, radiative-convective climate model (Peng *et al.*, 1987) reveal that a 10-percent change in upper tropospheric water vapor concentration may have an effect on global surface temperature comparable to a 10-percent change in the lower tropospheric water vapor amounts even though the absolute change in total water vapor content is very much less due to the relatively small quantities present at cold upper tropospheric temperatures (Arking, 1990). Thus, changes in upper tropospheric water vapor could potentially mitigate; e.g., drying leading to less warming in an overall climate warming scenario where boundary layer moisture and total vapor increase, or intensify the positive feedback associated with changes in boundary layer moisture (Lindzen, 1990; Betts, 1990; Del Genio *et al.*, 1991).

Regardless of our capability to accurately compute radiative fluxes, inadequate knowledge of atmospheric moisture content, particularly at middle and upper tropospheric levels, will necessarily compromise our confidence in those computations and our ability to define the present climate system. In fact, current models exhibit substantial differences in the global and regional water vapor amounts they maintain (Gutowski *et al.*, 1991a; Randall *et al.*, 1989). Moreover, our knowledge of upper tropospheric water vapor distribution and its variability is primitive at best (Rind *et al.*, 1991).

2.1.3 Climate Variability and Moist Processes

The past few decades have seen major advances in our understanding of climate fluctuations associated with the response of the atmosphere to slowly varying boundary conditions. Variations in sea surface temperatures (SST), in particular, have been linked to a wide range of tropical and extratropical climate anomalies. On interannual time scales, the El Niño/Southern Oscillation (ENSO) is the dominant mechanism of tropical variability involving major shifts in the position of the Walker and Hadley circulation cells (Lau *et al.*, 1983; Lau and Shen, 1988; Schubert and Park, 1991). ENSO (including the cold phase) has been linked to anomalous precipitation patterns world-wide. Regional-scale SST anomalies are also now considered to be responsible for major fluctuations in the sub-Saharan rainfall as well as significantly impacting seasonal climate in the middle latitudes (Ropelewski and Halpert, 1987). The general concept of remote response or teleconnection as an important factor in regional climate fluctuations has highlighted the need for a global perspective in understanding and modeling climate anomalies.

To a large extent, general circulation models (GCMs) have been successful in simulating gross features of the response to anomalous tropical sea surface temperatures. However, despite these successes, the inability of current GCMs to properly simulate many of the important details of the observed response, especially at the regional scale, suggests that a number of glaring problems remain (Sud and Molod, 1988). *To a large extent, these problems are associated with our poor understanding of and ability to model moist processes and their interaction with the circulation of the atmosphere.* In particular, the processes of cloud formation and precipitation and the associated latent heat release, energy transports and radiative forcing are not well understood.

The quasi-horizontal water vapor transport within the atmosphere is dominantly a large-scale process moving water vapor from its primary source regions over the subtropical and tropical oceans to fuel precipitating weather systems in tropical and middle latitudes, including those over the land masses. However, the scales of atmospheric circulation actually involved in cloud formation, latent heat release, and precipitation are relatively small by comparison (Houze and Hobbs, 1982). Condensation and precipitation in extratropical latitudes primarily occur within the frontal structure of cyclonic circulations and in mesoscale convection. In tropical latitudes, precipitation occurs within mesoscale convective systems associated with localized dynamic disturbances along the Inter-Tropical Convergence Zone. Subtropical precipitation is also dominated by deep convective systems in association with regional monsoon circulations. Within these weather systems, the vertical transports of water vapor and formation of individual clouds are typically organized at even smaller scales.

Improved knowledge of global water vapor fields, in conjunction with adequate descriptions of global cloudiness and precipitation, would enable evaluation of the treatment of moist processes within GCMs. ***However, improvements in the parametric representations of important physical processes for use in global climate models depend on an adequate understanding of the processes themselves. Highly detailed descriptions (at high spatial and temporal resolution) will be required to resolve the fundamental physical processes that are acting in the formation of clouds and precipitation.*** The heterogeneous character of water vapor distribution and moist processes reflected in the wide range of important scales presents a strong challenge to our capabilities to observe, analyze and model the global hydrologic cycle.

2.2 Scientific Objectives

To meet the overall goal of GVaP, the following scientific objectives have been identified:

1. To develop and apply algorithms to obtain an accurate global climatology of the horizontal and vertical distribution of atmospheric water vapor;

2. To develop and improve techniques to provide high vertical resolution global measurements of water vapor from satellites;

3. To improve knowledge of water vapor and its variability in relation to key hydrological processes by establishing a long-term climatology of the vertical distribution of atmospheric water vapor at selected sites and by conducting regional field campaigns in diverse climatological regimes;

4. To promote basic research contributing to an improved understanding of the role of atmospheric water vapor and its variability in meteorology, hydrology, and climatology.

Achievement of these objectives will significantly improve our knowledge of the distribution of water vapor in the atmosphere and our understanding of the important role of atmospheric water vapor and its variability in meteorological, hydrological and climatological processes. The objectives utilize and build on our present capabilities for observing water vapor (Section 3), for analyzing and incorporating water vapor observations into models, and for modeling moist processes, as well as realistic expectations for resultant future improvements in these respects. Further justification for each of these objectives is given below while the plan for achieving them is described in Section 4.

2.2.1 Global Climatology of Water Vapor

Although present global observing capabilities are limited in a number of important respects (Section 3), ***the value of even a relatively gross description of the global distribution of atmospheric water vapor is extremely high at this time.*** Present capabilities would allow derivation of column-integrated total water vapor or precipitable water (PW) from satellite observations over the oceans and radiosonde observations over the land areas with relatively good accuracy. Moisture in the planetary boundary layer, which dominates the vertically integrated total vapor, is maintained by a balance between horizontal moisture convergence, surface evaporation and convective transports (Betts and Ridgeway, 1988). The latter two processes are parameterized in GCMs.

Perhaps the weakest aspect of present cumulus parameterizations is their determination of precipitation efficiency, including vertical transports of condensate and vapor, evaporation of falling precipitation, entrainment of environmental air, detrainment of cloud water and vapor, and partitioning these processes into their cumulus and stratiform components. The monthly mean distribution of PW could therefore serve by itself as a sensitive indicator of deficiencies in the transport of water by moist convective schemes. These convective water transports and the associated heat transports play a critical role in the climate system through their effects on atmospheric circulation at all scales (Sud and Molod, 1988; Randall *et al.*, 1989; Del Genio *et al.*, 1991). If the distribution of water vapor were available on synoptic time scales as well, it could be used as a test of the models simulation of the quasi-equilibrium behavior of the atmosphere (and thus serve as a test of the cumulus mass flux closures). The monthly mean diurnal cycle of PW might also reveal problems in the interaction of convection, surface fluxes, and boundary layer parameterizations in GCMs (Randall *et al.*, 1991).

Furthermore, if available over an extended time period, a global PW climatology would probably be sufficient to detect changes in total atmospheric water vapor content anticipated in conjunction with potential or possible ongoing climate change. An accurate determination of PW could also be used to constrain and improve satellite-based retrievals of water vapor profiles. Similarly, incorporation of this information into assimilation of global data might also provide a basis for improved analysis of moisture fields and hydrologic processes. ***Efforts to resolve the corresponding vertical structure of the water vapor distribution, even if only at a relatively coarse vertical resolution, would be very useful in providing additional information about the gross features of convective and large-scale transports of water and our ability to define the global hydrologic cycle.*** Moreover, some measure of upper level moisture content is desperately needed to address issues related to the radiative role of water vapor in climate change (Lindzen, 1990; Betts, 1990; Rind *et al.*, 1991; Del Genio *et al.*, 1991).

2.2.2 High Vertical Resolution Global Satellite Observations

The critical need for accurate, high vertical resolution, global observations of atmospheric water vapor distribution derives from several factors.

First, water vapor concentration varies by several orders of magnitude within the troposphere in both the vertical and the horizontal directions. As a result, numerical models of the global climate system have long suffered from serious problems associated with computational transport of water vapor. This arises from the basic incompatibility of the relatively coarse vertical resolution used in the models with respect to resolving the strong and non-linear vertical dependence of water vapor concentration and transport within the atmosphere. Computational transport of water vapor occurs in the horizontal direction as well. Many of the numerical schemes currently adopted in climate models have difficulties dealing with the large horizontal gradients present in water vapor fields (Rasch and Williamson, 1990). Similar difficulties are associated with analysis schemes, particularly the model-based, four-dimensional, data assimilation (FDDA) schemes increasingly used for analysis of the atmosphere and the global climate system.

Second, the vertical structure of atmospheric relative humidity is often complex. This is evident in that many forms of extended stratiform cloud systems, such as stratocumulus, altostratus and cirrus clouds, form in relatively shallow layers ranging from 10^2 - 10^3 m in depth (Gedzelman, 1988; Starr and Wylie, 1990; Heymsfield *et al.*, 1991). Given the prevalence and areal extent of these cloud forms (Warren *et al.*, 1986; Warren *et al.*, 1988), we are forced to conclude that the corresponding lamination or stratification of atmospheric water vapor is a generic feature of atmospheric structure even at the large scale, although it is often somewhat masked by the overall strong vertical dependence of water vapor concentration at middle and upper levels. Such structure is more evident in the present observations when they are viewed in an isentropic analysis (Benjamin, 1989). In the lower troposphere, however, this structure is quite evident even in climatological profiles where the gradient of water vapor concentration between the boundary layer and the overlying free troposphere is large and highly concentrated over much of the planet.

Third, many important atmospheric hydrologic processes occur within rather shallow layers of the atmosphere and are extremely sensitive to the local moisture content in that layer. In addition to the formation of extended stratiform cloud layers which exert a very strong effect on the global radiative budget of the planet, the transfer of water vapor from the surface to the boundary layer and the exchange of vapor between the boundary layer and the free troposphere are critically sensitive to the local water vapor concentrations. The potential rates of surface evaporation, sublimation and evapotranspiration are driven by the difference between the near-surface vapor pressure and the saturation vapor pressure at the surface temperature. As with most hydrologic processes, an adequate description requires a number of parameters. In this case, these would include near-surface water vapor content and wind speed, surface temperature and water availability, and pertinent biospheric descriptors (Sellers *et al.*, 1986). Similarly, the rate transfer of moisture from the boundary layer to the free troposphere is critically sensitive to the gradient of water vapor concentration (and temperature) between the boundary layer and the overlying air and to the turbulent structure of the boundary layer that is also quite sensitive to the vertical structure of water vapor (and temperature) within the layer.

It must also be noted that the utility of water vapor observations for defining hydrologic processes is often complicated by dependence on relative humidity which is determined not only by water vapor concentration but also by temperature through the highly non-linear Clausius-Clapeyron relationship. Even a highly accurate observation of total water vapor content within a layer over which temperature varies appreciably (e.g., 20°C over 3 km) is quite ambiguous with respect to the relative humidity within the layer. This is especially problematic in situations where shallow moist layers are adjacent to much drier layers, as in the case of marine stratocumulus clouds and other extended stratiform clouds.

Given the importance of atmospheric hydrologic processes to the global climate and hydrologic systems, global analysis systems will increasingly attempt to resolve these processes and the associated moisture and temperature structure, especially in the context of FDDA. ***This will require that the assimilation models employ a vertical resolution compatible with the vertical scales characterizing these processes and the inherent vertical structure of the atmosphere. It will be absolutely essential that global observations be available for assimilation on a comparable vertical scale.***

Present satellite observations are completely inadequate in this respect. Even radiosonde observations produced by the operational international network are often inadequate in terms of vertical resolution in addition to their poor coverage of large portions of the planet. Regional (national) differences in humidity sensor characteristics and performance is another serious problem. Further refinements in present retrieval techniques may yield significant improvements, especially those utilizing combinations of data from various present and planned observing systems, e.g., AIRS/AMSU on EOS. These should be actively pursued. However, other technologies that may offer significantly increased vertical resolution, especially active remote sensing techniques, should be explored as possible future satellite-based observing systems.

Lastly, it must be emphasized that, in addition to providing coverage of the boundary layer, resolution of the middle and upper troposphere is an important characteristic of any global observing system in the context of climate change.

2.2.3 Improved Parameterization of Moist Processes

Water vapor plays a key role in all of the principal process parameterizations currently used in atmospheric models. It is the primary gaseous absorber of both longwave and shortwave radiation and is intimately connected to the prediction of cloudiness which strongly regulates the Earth's radiation budget in both the solar and infrared spectral regions. Formation of clouds through resolved (and sub-grid-scale) saturation also provides latent heat to the atmosphere and vertical transport of water, including stratiform rains and snowfall. In conditionally unstable situations, the water vapor distribution in the lower and middle troposphere is the primary determinant of the nature of moist convective activity and of convective precipitation. These convective processes cannot be explicitly resolved in current global- and regional-scale models. However, the effects of the associated vertical profile of latent heating and water transports are critically important (Randall *et al.*, 1989, Sud and Walker, 1990). Water vapor distribution also helps determine the buoyancy of unresolved turbulent motions and associated vertical transports, particularly in the tropical boundary layer. The state of the boundary layer, in turn, affects the rates of surface evaporation and evapotranspiration. Parameterizations of all of these processes use both the predicted (resolved) distribution of water vapor and assumptions about sub-grid-scale variability. Such assumptions, whether implicit or explicit (e.g., Sommeria and Deardorff, 1977; Sassamori, 1975), are presently rudimentary at best; e.g., no sub-grid-scale variability or a simple dependence on relative humidity for fractional large-scale cloudiness (Slingo *et al.*, 1989). Understanding the sub-grid-scale variability of water vapor in relationship to the resolved fields and the physical processes which operate is central to the entire parameterization approach.

In turn, each process significantly affects the prediction of the resolved fields. GCMs must adequately simulate phenomena on the large scale in which the parameterizations are embedded. Currently, discrepancies up to 100 percent exist between GCM-simulated and observed meridional energy transports (Covey, 1988; Stone and Risbey, 1990). Latent heat (moisture) transport is a major portion of the total transport. There is mounting evidence that the relatively low resolutions that have been used in GCM climate simulations are inadequate for accurately simulating the large-scale motion fields (Gutowski *et al.*, 1991b). The resulting inadequacies in horizontal convergence and vertical motions can severely impact the parameterizations. This is a dynamical issue independent of the question of the representation of the water vapor field but not separable from the parameterization issues. The models must be capable of adequately simulating the wind field given the correct smaller scale forcing. A second issue is adequate representation of the large-scale structure of the water vapor field itself in the models as discussed in Section 2.2.2. The explicit transport of water vapor in GCMs must be improved in parallel with parameterization development for progress to be achieved. Adequate data are required to validate both components.

Currently, the main uncertainty in determining tropospheric radiative heating rates in GCMs arises from the treatment of cloudiness--both in the prediction of cloud distribution and cloud radiative properties as well as in the parametric methods employed for the radiative transfer calculations (e.g., Mitchell *et al.*, 1989). Here, water vapor plays an indirect role through the prediction of cloudiness (below). The direct effects of water vapor on radiative heating rates, although much better parameterized than cloudiness effects, are nevertheless subject to considerable errors. These are primarily due to errors in model predictions of the vertical distribution of water vapor as determined by the resolved transports and by the transports arising from turbulence, large-scale condensation, and moist convection--each of which is parameterized. Uncertainties in the radiative properties of water vapor, particularly infrared continuum absorption/emission, may also be significant (Cutten, 1985; Varanasi, 1988).

Parameterizations of surface evaporation and turbulent mixing near the lower boundary fall into two categories: 1) those that attempt to resolve the vertical structure of the turbulence by using a closure model (usually of second order), and 2) bulk models, such as mixed-layer models, that attempt to predict only the depth and bulk properties of one or more fairly thick and homogeneous layers and assume that the main vertical structures consist of sharp gradients modeled at the interfaces between the layers. One of the main challenges for both types of models is in predicting the proper vertical distribution of water vapor within the boundary layer and in the transition region to the free atmosphere.

All processes involving condensation are poorly parameterized in GCMs. The so-called large-scale condensation, that occurs in conditionally stable situations, is the most straightforward (though not necessarily accurate) parameterization. Condensation is usually taken to occur above some critical relative humidity, and is evaluated from some simple function of relative humidity (or degree of supersaturation) and/or vertical motion. The resulting liquid water is then dropped instantly from layer to layer, with some re-evaporation occurring along the way. Better parameterizations of these processes are starting to appear in which condensed water (liquid and ice) is also kept as a large-scale prognostic variable in the GCM (Sundqvist, 1981). These will allow for more sophisticated large-scale condensation prediction schemes.

The parameterization of moist convective processes is one of the least understood problems in general circulation/climate modeling. Several parameterizations are currently available. Each attempts to adjust the predicted thermodynamic sounding to account for the effects of convective processes. In conditionally unstable situations, the convection parameterization effectively controls the thermodynamic structure of the free atmosphere. It mixes moisture and moist static energy between the boundary layer and the free atmosphere and between different levels within the free atmosphere. How it does this has a very strong effect on the distribution of relative humidity that the model produces and, consequently, also on the distribution of middle and upper level cloudiness and the distribution of radiative heating and cooling at remote locations. This adjustment can be based on an empirically determined or prescribed profile, e.g., Convective Adjustment, or a model of convective clouds and some closure that determines the vertical mass flux in the clouds, e.g., Arakawa-Schubert.

Detailed knowledge of the spatial and temporal structure of water vapor is essential to the development, improvement and verification of parameterizations for each of these processes. It is critical that the observations be as comprehensive as possible, including measurements of winds, temperature, clouds and other relevant parameters and that they resolve the scales at which the physical mechanisms operate.

Two basic approaches are recommended to provide the required knowledge. First, *intensive field experiments* in conjunction with modeling studies are needed to improve understanding of clouds, precipitation, radiation, and surface exchange processes. Appropriate process-oriented programs are already underway or planned, e.g., FIRE, STORM, SPECTRE, and HAPEX, ISLSCP and TOGA/ COARE, respectively. Each must necessarily rely on an accurate and detailed knowledge of atmospheric water vapor. Second, *continuous intensive observations* at specific climatologically important locations over time periods of a season or more are required to resolve the climatological characteristics of water vapor structure and variability in relation to other pertinent meteorological parameters. The planned Atmospheric Radiation Measurement program (ARM) has adopted this latter strategy. In either case, data with little or no vertical resolution such as total water content, will be of little use. Without detailed information, there is simply too much latitude in the knowledge base to meaningfully resolve the issues involved.

2.2.4 Basic Research on the Role of Water Vapor and its Variability

There is a need for basic research in support of each of the above objectives, including technology development, testing and intercomparison; development and evaluation of algorithms for application to satellite data; development and/or improvement and validation of models of various processes and models of global and regional hydrologic and climate systems; as well as the application of these tools. Analysis of water vapor observations on all scales is a key activity. However, there is one area in which a strong effort is particularly needed and which illustrates the basic requirement for the comprehensive effort embodied in GVaP. This is the assimilation of water vapor data into analyses of the global atmosphere/climate system.

The assimilation of water vapor observations has, in the past, been given low priority in comparison to the assimilation of mass and wind information in large-scale analysis systems. This is attributable to both the lack of reliable moisture data and the fact that global analysis has historically been driven by the requirements for improved numerical weather forecasts. Weather forecast models require initial fields that lead to the best forecasts. Inclusion of good data can, in fact, produce a degradation in forecast accuracy if it is not consistent with the model physics. In practice, current numerical weather forecasts are not strongly affected by the initial moisture conditions since forecast models rapidly produce moisture fields that are consistent with the initial mass and wind information and model parameterizations of moist processes. There is no requirement that the moisture fields be consistent with the available water vapor observations.

Even in the tropics, where details of the moisture distribution can dramatically alter the response of convective parameterizations (which in turn can quickly alter the moisture distribution), the general trend has been for a "hands-off" approach to the assimilation of moisture data since internally consistent moisture fields have been shown to dramatically reduce the spin-up of vertical motion and precipitation fields.

On the other hand, climate studies have very different requirements for moisture analysis. To be useful for climate studies such as analyzing the global hydrologic cycle and radiative heat budget, it is important that the atmospheric water vapor field be accurately known. Moreover, there is a clear need to remove present biases in climate models (that also appear in forecast models) which appear strongly tied to the parametric treatment of convection and clouds/radiation; e.g., an atmosphere which is significantly too dry or too wet. Efforts to correct such problems rely on an accurate knowledge of the distribution of atmospheric water vapor. This has renewed efforts and interest in improving moisture analyses for climate applications.

The difficulties of performing analysis of water vapor distribution for forecasting or climate analysis applications are well-illustrated by the very substantial differences found in the tropics between the operational analyses produced by the United States National Meteorological Center (NMC) and the European Centre for Medium-Range Weather Forecasts (ECMWF). Furthermore, analyses from the same center show large systematic changes in even the gross features of water vapor distribution coincident with major changes in the forecast-analysis system (Trenberth and Olson, 1988). This is unacceptable for climate studies.

The current sources of moisture data which have been used in data assimilation schemes include radiosonde reports, satellite measurements and "bogus" data derived from satellite cloud data as well as surface-based observations including cloud amount and weather type. All of these data have problems (Section 3) either in terms of accuracy, horizontal and/or vertical resolution, or horizontal and/or vertical coverage (or combinations thereof). Often, only radiosonde data is used. The lack of sufficient global coverage or reliable moisture data makes the implementation rather ad-hoc. There are insufficient moisture data in both quality and quantity to adequately define the spatial correlation structure of the forecast errors as well as the forecast error growth. These aspects of the forecast errors are crucial for determining the optimal combination of the first guess and observations. ***In practice, what little moisture information enters the analysis scheme is either ignored or quickly rained out by the model since it is generally not consistent with the model's climate.***

Improvements in the assimilation of moisture fields will require substantial efforts to 1) increase the quality and quantity of available moisture observations, 2) improve the treatment of the explicitly resolved transports of water vapor, 3) improve parameterizations of moist processes with emphasis on reducing the sensitivity to data errors and reducing model bias and 4) develop techniques for merging the observations with the model fields that minimize the initial shock and the spin-up time of the model.

2.2.5 Summary

Dramatic improvements will be needed in global water vapor observing systems and in our ability to use this data before we will be able to determine the atmospheric hydrologic cycle with any degree of certainty. Obtaining data of sufficient quality and resolution to improve our understanding of important physical processes will require even greater strides in terms of accuracy and resolution. Development and validation of suitable parameterizations for use in global climate and Earth System models depend on such improvements. Recent progress in remote and *in-situ* sensing of atmospheric water vapor shows good promise for obtaining the required observations. Efforts to develop and apply these technologies must be supported and enhanced. Only in this way will meaningful progress be achieved.

3. Water Vapor Measurement Capabilities

Any improvement in our understanding of the role of atmospheric water vapor in hydrologic processes will rely heavily on high-quality measurements of moisture on temporal and spatial scales appropriate to address the problems under study. Methods to measure atmospheric water vapor include upper air sondes, satellite observations, surface and airborne remote and *in-situ* sensors. Each of these have strengths and weaknesses, as described in more detail here.

3.1 Upper Air Sondes

Routine measurements of atmospheric water vapor are made with the global upper air balloon sounding network. This capability has been the only source of global water vapor data over the last 50 years. The geographical spacing of the upper air soundings is generally quite uneven--about 400 km in North America, somewhat less in western Europe, but significantly greater over most other land areas. Sounding stations are extremely sparse over the vast oceanic regions of the globe where large areas are virtually unobserved and almost all soundings are made from island stations. Shipboard soundings are made but are neither routinely scheduled nor dense enough to be generally useful for other than forecast applications. Routine moisture and temperature soundings are usually made at 12-hour intervals over North America and western Europe but often less frequently elsewhere.

The quoted accuracy (rms error) of the standard U.S. National Weather Service (NWS) sonde (carbon hygristor sensor) is ±5 percent when the relative humidity exceeds 20 percent (Hoehne, 1980; Pratt, 1985). Even though the sensor is sensitive at low relative humidities and at cold temperatures (albeit less so than in its optimal operating range), the established procedures for processing the raw data (transfer equation) give the improper impression that the sensor is totally insensitive (Schmidlin, 1989). When the observed relative humidity is less than 20 percent, a value near 20 percent is generally reported (moist bias). Moisture data are not even reported at temperatures colder than -40°C. *Consequently, very few observations are available in the upper troposphere, especially at tropical latitudes* (e.g., Peixóto and Oort, 1983; Blackwell *et al.*, 1988). In addition, the vertical resolution of routine soundings is often insufficient to resolve the detailed relative humidity structure associated with development of stratiform clouds, particularly in the middle troposphere (Starr and Wylie, 1990). *This lack of vertical resolution is not inherent.* Implementation of appropriate procedures for sampling and reporting the data would result in substantial improvements in this respect (Finger and Schmidlin, 1991).

The accuracy and precision of upper air moisture measurements vary significantly from one country to another depending on the sensor and/or instrument used (Nash and Schmidlin, 1987; Schmidlin, 1989). Instrument-specific problems are known to exist but are poorly documented. For example, the carbon hygristor (NWS), goldbeaters skin (U.K. and U.S.S.R.), and humicap sensors (western Europe) show notable differences in response at both high and low humidities. These differences may amount to more than 20 percent in the observed relative humidity and tend to be temperature (height) dependent. Performance characteristics at cold (< -30°C) temperatures are particularly uncertain. Wetting, icing, or solar heating of the sensor can also lead to systematic (non-random) errors of significant magnitude which differ from one sensor type to another. For example, observations with goldbeaters skin sensors after the instrument has emerged from a rain layer tend to be larger by 20 percent or more when compared to the other sensors. This wetting effect may persist for a distance of 1 to 3 km or more above the cloud.

The reporting practices also vary from one country to another. For example, humidities are reported at very high vertical resolution over the entire sounding in western Europe and other areas where the humicap sensor is used. Thus, data are reported at temperatures colder than -40°C. As noted above, however, the error characteristics at temperatures colder than -30°C are not well-established although performance does appear to be degraded in comparison to lower (warmer) levels as is also the case with the NWS sonde. These regional differences in both error characteristics and reporting practices can lead to analysis of false regional differences or anomalies.

In summary, the present upper air sounding system has numerous shortcomings with respect to defining hydrologic processes, particularly since a number of very important processes occur predominantly at the mesoscale. Shortcomings include:

- Inadequate horizontal resolution and coverage, especially over the oceans.
- Grossly insufficient temporal sampling.
- Uncertain data quality including significant random errors (precision) and non-random, environment-dependent errors (bias).
- Variation in sensor type, calibration and data analysis leading to regional variations and further uncertainty in data quality.
- Inadequate vertical resolution in the middle troposphere.
- Almost no data in the upper troposphere.

These limitations have long been recognized. Experiments have recently been conducted to compare different types of sensors under various environmental conditions (Schmidlin, 1989). The need for a standard reference instrument has also long been recognized, but none have ever acquired universal acceptance. Development of an advanced "calibration" sonde package is presently being considered. It is clear that more work is required to improve and standardize this important source of global water vapor data (Finger and Schmidlin, 1991).

3.2 Present Satellite Capabilities

Satellite observations provide a means to monitor global moisture distribution. Horizontal resolution and geographical coverage are far superior to that of the routine upper air sounding network (radiosondes). The current operational sounding system (TOVS) on the sun-synchronous, polar-orbiting NOAA satellites provides asynchronous information on water vapor profiles at a temporal resolution of 6 hours (two-satellite system). Although geostationary platforms (GOES and METEOSAT) offer temporal resolution capable of resolving the development of mesoscale features, limited quantitative information on water vapor distribution is derived from the present operational sounding system (GOES/VAS) which was designed primarily for temperature sounding. Vertical resolution is quite limited with either of these operational sounding systems because of the use of only a few, relatively broadband, infrared channels with sensitivity to water vapor. The limb-scanning SAGE II instrument produces limited amounts of data in the lower troposphere but has been used to produce accurate profiles in the upper troposphere and stratosphere with superior vertical resolution.

3.2.1 TOVS

The current operational polar-orbiting infrared/microwave sounding system (TOVS) was designed primarily to determine the global distribution of atmospheric temperature and moisture profiles (Smith *et al.*, 1979). Information about vertical distribution of water vapor is obtained primarily through observations in five broadband infrared channels (HIRS-2) between 6 and 14 μm. However, radiances in these channels are also significantly affected by the profile of atmospheric temperature and/or surface temperature (window channels) within the field of view. All these factors must be taken into account (and accurately retrieved) to produce an accurate retrieval of the vertical distribution of water vapor. In addition, the radiance observations are strongly affected by clouds and, as a result, retrievals are not produced in overcast areas (some information can be derived above cloud top). Profiles can be derived in situations of partial cloud cover, but the results are only indicative of conditions in the cloud free areas of the scene. The concurrent microwave (MSU) observations on TOVS enable coarse-resolution temperature soundings to be generated for overcast scenes but no profiles of water vapor are obtained.

Temperature and moisture profiles from TOVS are operationally produced and archived by NOAA-NESDIS. Until recently, these profiles were produced via purely statistical methods; i.e., regression of observations against radiosonde reports (Smith and Woolf, 1976; Smith *et al.*, 1979). Since the dependence of satellite-observed radiances on the distribution of water vapor is highly non-linear and fairly sensitive to errors in the retrieved temperature structure, the operational data base of statistical retrievals of water vapor from HIRS data (prior to September 1988) is not generally considered to be useful. Another consequence of the use of a statistical retrieval scheme is that retrievals are not produced above 300 mb (~9 km) because of lack of correlative radiosonde humidity observations above this level. The present operational retrieval system is a physically based technique similar to that described below.

A physically based technique for analysis of HIRS-2/MSU data has been developed at NASA and is being used to produce a multiyear global data set (reprocessing of archived radiance data) of temperature and moisture profiles, as well as surface and cloud parameters, and total atmospheric ozone burden (Susskind *et al.*, 1984; Susskind and Reuter, 1985; Susskind *et al.*, 1987). The analysis method utilizes output from a suitably initialized 6-hour run of a GCM for the initial guess used in the retrieval. Although the retrievals are influenced by the first-guess humidity field, especially at low levels, improvement on the initial guess is found at all levels, both in terms of absolute accuracy as well as realism of patterns (Reuter *et al.*, 1988). Typical accuracy (rms) compared to radiosonde observations is ±20 percent for total precipitable water vapor, and ±25 to 40 percent for vertically integrated water vapor in three layers (1000 to 700 mb, 700 to 500 mb, and 500 to 300 mb) where accuracy decreases with altitude. Precipitable water patterns above 300 mb also appear reasonable but cannot be verified given the lack of correlative observations at those levels. Interannual differences of upper tropospheric water vapor have been shown to be highly correlated with interannual differences of high-level clouds and precipitation in the tropics. This lends credence to the upper level moisture retrievals, at least in a qualitative sense.

3.2.2 VAS

Imagery from the 6.7 μm "water vapor" channel on GOES/VAS and METEOSAT is a widely used product, having been applied to depict such phenomena as cyclogenesis and tropopause folding (Uccellini *et al.*, 1985; Reed and Albright, 1986; and Young *et al.*, 1987), initiation of convection and severe weather (Rodgers *et al.*, 1983; Petersen *et al.*, 1984; Fuelberg *et al.*, 1991), tropical cyclones (Velden, 1987) and the effects of tropical convection on upper tropospheric water budget (McGuirk *et al.*, 1987). A VAS channel at 7.2 μm gives a similar view. Although the animated imagery is popular with operational forecasters, it still is probably underutilized because the complex dynamic and thermodynamic processes that produce the observed patterns are poorly understood. Precipitable water fields have been obtained from the "split window" channels at 11 and 12.7 μm (Chesters *et al.*, 1987) which are affected by contamination due to water vapor.

As with HIRS-2, these and a few other channels, that are used primarily for temperature sounding but which have some sensitivity to water vapor contents, can be used to derive profiles of water vapor. A physically based retrieval is used operationally (Hayden, 1988) although statistical methods have also been employed (Lee *et al.*, 1983). Because of the inherent limitations that are similar to those of TOVS, the vertical resolution of these soundings is relatively coarse. The observed strong mesoscale variability of atmospheric water vapor and the coarse spatial resolution of the verifying conventional upper air sounding network have hindered efforts to quantify the accuracy of the moisture soundings. The sensitivity of the VAS channels to upper tropospheric water vapor has proven particularly problematic in this respect (Blackwell *et al.*, 1989). Recently, Fuelberg and Olsen (1991) showed that the standard deviation of dew point differences ranged from 2.9°C to 6.9°C depending on pressure level based on analysis of over 1000 VAS-RAOB pairs.

3.2.3 SMMR-SSM/I

Some success has been obtained in monitoring total column-integrated atmospheric water vapor over ocean using microwave instruments with a channel sampling a weak water vapor absorption feature around 22 GHz and a channel for sampling adjacent, more transparent spectral bands (e.g., 19 GHz and/or 37 GHz) including NEMS, SMMR on Nimbus-7, and SSM/I on the current DMSP satellite (Prabhakara *et al.*, 1985; Ardanuy *et al.*, 1987; McMurdie and Katsaros, 1991). However, no information is given over land, sea-ice, or in areas where precipitation is occurring. In addition, no information on the vertical distribution of water vapor is obtained. Although absolute calibration is a problem, the accuracy of total column water vapor retrievals is generally thought to be better than ±10 percent.

3.2.4 SAGE II

The SAGE II instrument on ERBS has been making routine measurements of water vapor concentration with 1-km vertical resolution from the mid-troposphere to 45 km since October 1984. A solar occultation technique is used which has the inherent capability of self-calibration, high accuracy and high vertical resolution making it excellent for long-term trend detection. Measurements are made down to cloud top with a horizontal resolution of about 200 km. Masurements are obtained down to the 5-km level about 50 percent of the time (Rind *et al.*, 1991). Presently, SAGE II is making the only global stratospheric measurements of water vapor and producing the only global climatology at those altitudes. In addition, it is producing an upper tropospheric global climatology (albeit for non-cloud regions) including tropical regions. About 1000 profiles are observed each month. These data should be more widely exploited. The data could be used as correlative (validating) data or first-guess data to constrain retrievals from other satellite observations.

3.3 Future Satellite Capabilities

Ongoing efforts to improve water vapor products derived from present satellite observing systems will yield some progress over the next few years through improved intercalibration of satellite sensor/algorithm systems, routine application of physically based retrieval methods, and efforts to integrate information from various sensors/platforms. Major advances are unlikely given the limitations of present infrared sounders (only a few broadband water vapor sensitive channels). However, more significant advances are anticipated in conjunction with the availability of data from various planned improvements to the operational satellite-based sounding systems.

3.3.1 Operational Polar-orbiting Satellites

The NOAA K - N series of satellites to be launched beginning in the 1994 time frame will carry the Advanced Microwave Sounding Units (AMSU) - A and B in addition to an improved infrared sounder (HIRS-3). AMSU-B is a 5-channel microwave radiometer sampling the water vapor absorption band at 183 GHz. This will allow for significantly improved water vapor profiling capabilities, especially in the boundary layer over oceans, in the upper troposphere, and under overcast conditions. Data will also be available from the suite of microwave instruments, such as the SSM/I and SSM/T-2 (similar to AMSU-B), that are scheduled to be flown on future DMSP satellites in this time frame.

3.3.2 Geostationary Satellites

Near-term improvements in the geostationary moisture observing capabilities will occur with the launch of the GOES I - M satellite series (1992-1997). The GOES I - M series will have separate imagery and sounding systems allowing greater capability in both modes. The imager will provide measurements in the infrared windows at 11 and 12.7 μm (split-window) at 4-km resolution and in the water vapor absorption band at 6.7 μm at 8-km resolution. These data will be available over regional areas at high temporal resolution. The sounder will be substantially improved over the previous VAS with a total of 19 channels, similar to those on HIRS, for temperature and moisture sounding. A total of six of these channels, including the window channels, are sensitive to atmospheric water vapor content. As a result, moisture sounding capabilities will be improved in quantity and quality with respect to previous VAS capabilities.

3.3.3 EOS

The first polar platform for the EOS, to be launched around 1998, will carry both AIRS and MODIS along with AMSU-A and B. AIRS is a high-spectral-resolution infrared sounder with a spatial resolution of 15 km--the same as that of AMSU-B. The AIRS observations should permit retrieval of water vapor profiles up to the 100-mb level. An accuracy of about ±15 percent is expected for retrievals of precipitable water for layers that are 2-km in depth. A total column-integrated precipitable water accuracy of about ±5 percent should be achieved. As with HIRS, the soundings will be produced only in clear or partly cloudy areas (up to 70 percent cloud cover). Some information may also be obtained for levels above cloud top in nearly overcast scenes. The AMSU-B observations will provide more limited sounding capability for overcast scenes, including within and below cloud. MODIS has the same intrinsic sounding capability of HIRS, but with a spatial resolution of 1 km. This should allow for a better ability to monitor small-scale water vapor distribution, especially in the vicinity of clouds. Optimal moisture profiling results are to be achieved from the use of AIRS, AMSU-B and MODIS as a composite sounding system in conjunction with conventional (radiosonde) observations.

3.3.4 SAGE III

An improved SAGE instrument, SAGE III, is being considered for flight as part of EOS and/or an earlier Earth probe. It will measure water vapor with increased spectral resolution and dynamic range allowing for 1-km vertical resolution from the lower troposphere (for cloud-free limb paths) to 50 km at ±5 to 10 percent accuracy. In addition to making measurements during solar occultations, SAGE III will also be able to make measurements during lunar occultations which greatly increases the latitudinal and time of day coverages in comparison to SAGE II (50 percent increase in the observations per month). Density is also measured so that mixing ratio and relative humidity can be calculated without the need for ancillary data.

3.3.5 Lidar

An active satellite-based moisture sounding system likely will be feasible in the near future. Simulations of a lidar sounding system using the differential absorption technique indicate that good accuracy (±5 percent) and high vertical resolution (1 km or better) can be achieved (Ismail and Browell, 1989). Development of this technology is highly desirable given the inherent advantages in comparison to passive sounding techniques (Section 4.2).

3.4 Surface-based and Airborne Remote Sensing

Surface-based and airborne remote sensing offer the advantage of high temporal and/or spatial resolution. Frequent sensor calibration is possible. At present, there is no global observing capability as only a limited number of such systems have been built. In some instances, high horizontal resolution can be achieved over a very limited area by deploying multiple surface-based systems. However, some of these systems are virtually unique at the present time. Observations from aircraft enable the high temporal resolution to be translated into high horizontal resolution but are subject to the sampling constraints imposed by the platform; i.e., limited flight duration and asynchronous spatial sampling.

An inherent problem in surface-based remote sensing of atmospheric water vapor profiles is that the bulk of the water vapor generally resides close to the surface in the boundary layer. Thus, the strength of the signal source decreases with height while signal attenuation is strongest near the surface. In the case of passive remote sensing techniques, this effect is strongly amplified by the effects of decreasing temperature (source strength decreases with temperature) and pressure (line widths decrease with pressure) with height. Thus, the very effects that enable passive determinations of profiles from satellites strongly limit the possibilities of profiling from the surface, especially above the first 1 or 2 kilometers. However, surface-based sensors do not have to contend with a highly variable surface emission, with the consequence that integrated quantities, such as precipitable water vapor, can be accurately determined. Moreover, obscuration by clouds does not prevent observations of the boundary layer--where most of the moisture resides--as it does for satellite systems. The continuity in time of these sensors is such that derived products may be used for satellite validation and, perhaps, calibration (Westwater *et al.*, 1989a). However, the limitation of poor vertical resolution is a severe one that is common to passive sensors, either from upward- or downward-looking systems. Finally, surface-based systems are not subject to the more demanding constraints imposed by satellite and aircraft platforms (power, weight, antenna size, etc.).

3.4.1 Microwave Moisture Measurements

Surface-based microwave radiometers have been developed for the purpose of monitoring atmospheric water vapor. Present capabilities enable estimation of total column-integrated water vapor (precipitable water vapor) with accuracy comparable to that achieved using current radiosondes: temporal resolutions of 1 second to 2 minutes are achieved (Hogg *et al.*, 1982; Westwater *et al.*, 1989b). Measurements may be obtained over land surfaces where microwave satellite observations are ambiguous. As in the case of the satellite microwave observations, retrievals are not obtained in areas of precipitation. Otherwise, clouds are not a problem and vertically integrated cloud liquid can also be derived (Cahalan and Snider, 1989; Fairall *et al.*, 1990). Some indication of the vertical distribution of water vapor can be estimated using statistical analysis based on regressions with upper air soundings (Askne and Westwater, 1986). However, capabilities for detection of upper- and middle-level water vapor concentrations are quite limited.

Airborne microwave sensors (AMSU) also have been developed in preparation for EOS. It is anticipated that these instruments will provide improved capabilities for observing atmospheric water vapor profiles in comparison to present satellite capabilities. However, problems arising from the high variability of land surface background will limit applications to over-water environments. Experiments conducted over oceans in the past few years have shown that vertically integrated water vapor contents can be retrieved for up to 4 or 5 individual layers between the 300- and 1000-mb levels. Accuracy range from ±10 to 40 percent with the larger uncertainty being at higher altitudes. Profiles can be estimated even over land surfaces with a possible exception of the lowest layer (below ~ 2 km). Retrieval of water vapor profiles over moderate cloud cover has also been attempted with reasonable success. However, as is the case with satellite-based observations, validation is difficult.

3.4.2 Infrared Moisture Measurements

A surface-based, high-spectral-resolution infrared sounder has been shown to be sensitive to water vapor in the planetary boundary layer. However, there is little potential to derive information on water vapor above the boundary layer using this approach.

The same system (High-spectral-resolution Interferometer Sounder, HIS), which has spectral resolution comparable to the AIRS instrument proposed for the EOS, has been deployed on a high-altitude aircraft (NASA ER-2) and has yielded superior water vapor retrievals in terms of accuracy and vertical resolution in comparison to those derived from present satellite observations (Smith *et al.*, 1987; Rivercomb *et al.*, 1987). As in all infrared techniques, cloud obscuration is a significant problem. However, in comparison to satellite observations, this is at least partly compensated by the much smaller field of view relative to cloud features enabling observations to be obtained in situations of near overcast that would appear totally overcast at the spatial resolution of typical satellite observations; i.e., looking through the holes in the cloud field. Nonetheless, the basic limitations of infrared techniques that constrain satellite observations are also applicable here.

3.4.3 Lidar Moisture Measurements

Two active optical sensing techniques (lidar) have been developed to measure atmospheric water vapor profiles. They are the Raman lidar and differential absorption lidar (DIAL) techniques. Both techniques yield high vertical resolution. Neither technique will allow probing of cloudy volumes, although as in the case of the airborne HIS (above), adequate holes are often present to enable observations even in seemingly overcast conditions.

3.4.3.1 Raman Technique

The Raman technique observes very weak Raman scattering of a transmitted laser pulse by atmospheric water vapor, and it was first applied to these measurements over 20 years ago. Surface-based systems have been developed, and they have produced useful atmospheric information during nighttime observations (Melfi and Whiteman, 1985; Melfi *et al.*, 1989). Integrated nighttime measurements over several minutes (~1000 shots) provide accurate water vapor profiles (± 0.5 g kg^{-1}) to an altitude of 7 km (or cloud base) at a vertical resolution of about 150 m. Upgrades to the present technology (in progress) should permit observations to above 10 km at night and limited capabilities for daytime operations. Daytime capabilities are projected to allow measurements of water vapor up to an altitude of about 4 km. Longer integration times can also be used to compensate for the weak backscattered signal and to extend the vertical domain and/or daytime capability. As is generally typical for active remote sensing techniques, probing of the near-field is difficult due to the alignment requirements between the laser source and receiver. As a result, observations in the lower boundary layer (lowest few hundred meters) are of questionable value. Cloud obscuration and precipitation are additional limiting factors.

3.4.3.2 DIAL Technique

The Differential Absorption Lidar (DIAL) technique uses the difference between the range-dependent absorption of backscattered laser beam energy at two frequencies to infer a water vapor concentration profile. This technique has been used for ground-based measurements of water vapor profiles (Browell *et al.*, 1979; Cahen *et al.*, 1982). An airborne DIAL system has also been built and operated in a down-looking mode (Browell *et al.*, 1991). Daytime and nighttime water vapor distributions over continental and maritime regimes have been measured with a vertical resolution of about 300 m and an accuracy of better than ±10 percent from near the surface to an altitude of 4 km. To achieve this accuracy, an averaging time of 1 minute was used, which represents a horizontal resolution of about 6 km. Measurements to near 10-km altitude are possible in either a down- or up-looking mode of operation using the current water vapor absorption lines near 727 nm. Future measurements to 18-km altitude will be possible using water vapor lines near 940 nm with the lidar operating in an up-looking mode.

The DIAL technique is suitable for future spaceborne lidar measurements of global water vapor distributions in the lower atmosphere with high vertical resolution (< 1 km). As in the case of passive methods, this technique is best suited for down-looking operation where source strength and signal attenuation increase with range. However, the capabilities for up-looking operation from either the ground or aircraft should be much superior to those of passive techniques. Use of atmospheric water vapor absorption lines of different strengths permits optimized measurements to different altitudes under a variety of atmospheric conditions (Ismail and Browell, 1989). A water vapor DIAL system capable of autonomous operation from a high-altitude aircraft is presently under development (Lidar Atmospheric Sensing Experiment, LASE) and represents the next step toward development of a spaceborne system.

3.5 Airborne *In-situ* Methods

Several types of *in-situ* water vapor measuring systems have been deployed on research aircraft. These include:

a) Dew point hygrometer (chilled mirror),

b) Lyman-alpha hygrometer (absorption),

c) Lyman-alpha hygrometer (fluorescence),

d) Microwave reflectometer,

e) Humicap sensors, and

f) Cryogenic collection.

Several (but not all) of these instruments have the capability of measuring water vapor concentration to the accuracy required for climate and meteorological applications including investigations of hydrologic processes at the mesoscale. Successful operation, however, requires careful and continuous attention to calibration.

In the lower troposphere where water vapor contents exceed 0.2 g kg^{-1}, instruments (a), (b), (d), and (e) can be used and can achieve an accuracy of ±5 to 10 percent. The chilled mirror (a) is the standard instrument under these conditions while (b) is used to take high data-rate turbulence observations (0.1-s sampling/response time). Instrument drift has been a major drawback for Lyman-alpha absorption hygrometers (b). In the upper troposphere and lower stratosphere where water vapor concentrations may be as low as 1 ppmv, instruments (a), (c), and (f) are capable of achieving ±5 to 10 percent accuracy. Method (f) is cumbersome and useful only for calibration purposes or in combination with other trace gas detectors. The chilled mirror device (a), when modified to utilize cryogenic cooling, is capable of frost point measurements down to -90°C with an accuracy of ±1°C and a response time of between 1 and 10 seconds. The Lyman-alpha fluorescence device (b) is capable of achieving an accuracy of about ±10 percent in even the driest parts of the atmosphere (±0.5°C in terms of frost point) but requires careful and frequent calibration to achieve this accuracy.

The continued development and calibration of these airborne instruments is of *very high priority. The lack of correlative "ground truth" moisture observations of sufficient absolute accuracy and* *suitable sampling characteristics has been the major factor impeding efforts to characterize and improve global satellite-based observing systems and radiosonde sensors.* Meaningful cooperation between NASA, NOAA and NCAR is especially important in this regard.

Beyond the important applications for *in-situ* calibration of remote sensors based on satellites, aircraft and the surface as well as radiosonde sensors, these airborne instruments are well-suited for studies of hydrologic processes requiring high temporal and spatial resolution of relatively transient mesoscale phenomena. Research aircraft provide the unique capability of making simultaneous observations of the multiple parameters usually required to resolve hydrologic processes including wind, temperature and moisture; numbers, sizes and compositions of aerosol and cloud particle populations; trace gas concentrations; and spectrally-resolved radiances and radiative fluxes. In combination, such observations provide a basis for improving understanding of various fundamental hydrologic processes in the atmosphere.

3.6 Conclusions

The challenge is to take full advantage of these methods and acquire the necessary data on atmospheric water vapor and its spatial and temporal variance. As mentioned in Section 2, increased understanding of the role of water vapor requires investigations ranging from local intensive observational campaigns for improving model parameterizations to the development of a global climatology of water vapor matching the temporal, vertical and horizontal requirements of GCMs. Combinations of various measurement methods and improvement of others will be needed to meet this challenge. The following provides some recommendations.

Water vapor measurements from space should be given increased emphasis. Improved methods and analysis techniques must be developed. Clearly, the most dependable ground truth, the upper air sondes, need to be upgraded to provide reliable and accurate water vapor profiles throughout the troposphere and around the world. Continued development of methods to retrieve water vapor profiles using passive infrared and microwave radiometric observations should be pursued leading to the EOS. In the long run, active optical (lidar) methods should be developed and deployed on spacecraft to provide the high vertical resolution required to adequately resolve the water vapor structure associated with hydrologic processes in the atmosphere. In the meantime, efforts to develop, improve, calibrate, and apply instruments and techniques to obtain the required water vapor measurements to support these global observing activities as well as to provide a basis for improving our understanding of various hydrologic processes must be continued and expanded. These include the technology and techniques for making remote and *in-situ* observations from the surface and from aircraft.

4. Research Plan

A research strategy to improve our quantitative knowledge and understanding of the role of water vapor in the Earth's hydrological and climatic processes must incorporate strong coupling of observational and modeling activities. Observations are the key element in promoting advances in our knowledge of the atmospheric hydrologic cycle and the global climate system. Models represent an integration of the knowledge gained from observations and theory and provide the means to understand complex and highly interactive systems as well as guidance in terms of key observational requirements. Models also provide a possible means for assessment and prediction of potential change. Analysis is the bridge between observations, theory and models.

The strategy to achieve the four central GVaP science objectives (Section 2.2) is described in the following subsections. Collecting and analyzing observations in concert with modeling activities are integral to achievement of each objective.

4.1 Global Climatology of Water Vapor

4.1.1 Precipitable Water Vapor (PW)

Satellite-borne microwave radiometers sampling at a frequency of about 22 GHz which respond to lower tropospheric water vapor, such as the SSM/I instrument on the present (and planned) DMSP satellite as well as the prior SMMR instrument on Nimbus-7, provide a means to retrieve PW over radiatively cold oceanic backgrounds. An additional channel is required to estimate the effects of surface roughness on the background brightness temperature at 22-GHz as well as to detect/confirm contamination by precipitation. SSM/I has provided nearly global coverage every 2 days although the retrieval of PW is not possible over land areas due to the high emittance of land surfaces (too strong a background signal) and the strong dependence (variability) of surface emittance on soil moisture. Conventional radiosonde observations provide coverage over many (but definitely not all) major land areas on a daily basis. The accuracy of PW estimates derived from SSM/I are believed to be roughly comparable to that of radiosonde observations. In addition, retrievals of PW can be made using HIRS-2/MSU observations (Section 3.2.1) and the future HIRS-3/AMSU-B system (Section 3.3.1). Although somewhat noisier and limited by cloud obscuration, these data would provide nearly global coverage on a daily basis over both land and ocean areas.

Thus, a relatively accurate determination of the global distribution of total vertically integrated atmospheric water vapor content or precipitable water is presently possible. Coverage over oceanic areas would be limited to non-precipitating regions. Although a daily product could be derived, a weekly or monthly global product would be more consistent with DMSP (SSM/I) satellite sampling (orbital precession) characteristics and would be a more statistically robust product. The diurnal cycle could be resolved on a monthly basis.

It is recommended that a coordinated effort be made to derive a monthly climatology of the global distribution of PW using a combination of satellite observations, such as SSM/I and HIRS/MSU, and radiosonde observations. This climatology must span a multiyear period and would be highly complementary to other efforts to determine global climatologies of cloudiness (ISCCP) and precipitation (GPCP). It is important that this analysis be as complete as possible (ocean and land areas) and that some means of estimating PW within oceanic areas of precipitation be developed; e.g., assuming saturation over some detected rain-layer depth in conjunction with temperature estimates from higher frequency microwave measurements. Furthermore, *the accuracy of the derived product must be well-established* (Section 4.5) and the diurnal cycle should be resolved. It must be emphasized that the satellite data required to begin constructing such a climatology presently exist (SSM/I, HIRS-2/MSU and possibly SMMR).

A monthly product over a multiyear period would have great value in evaluating and improving the performance of global climate models (Section 2.2.1) and in assessing possible changes associated with potential changes in the climate system (Section 2.1.2). Intercomparison of the results of GCM experiments, especially with respect to the annual cycle of water vapor distribution and the response to corresponding SST anomaly patterns observed during the span of the water vapor climatology, will be needed. Sensitivity studies to gauge the effects of model parameterizations of cumulus convection, boundary layer development and surface exchange are also highly recommended (e.g., Sud and Walker, 1990). Resolution of the diurnal cycle of water vapor distribution would be particularly beneficial in these respects (Randall *et al.*, 1991).

Archiving the retrievals at the original resolution would permit their utilization for studies aimed at improving present capabilities for assimilating moisture data into operational analyses (FDDA) of the atmosphere/climate system (Section 2.2.4). These activities are essential, especially in the context of preparing for EOS data. In some respects, these investigations parallel and benefit from the recommended GCM studies; i.e., performance evaluation of parameterizations. However, a capability to vertically resolve--even coarsely--the global distribution of water vapor is a more fundamental requirement here. If the PW retrievals are archived at original resolution, then it may be possible to utilize this information to constrain and significantly improve retrievals of water vapor profiles derived from present and future NOAA operational satellite sensors (below).

4.1.2 Vertical Distribution of Water Vapor

It is clear that achievement of a vertical resolution in global (satellite-based) water vapor profile observations comparable to present (~10 levels in the troposphere) and future (more than 20 tropospheric levels) GCMs is highly desired (Section 2.2.2). Given the present and planned satellite observing systems (Sections 3.2 and 3.3), this will not be possible at least until EOS-A is launched toward the end of this decade. Although EOS will provide enhanced vertical resolution, it is quite possible that even EOS will not be able to provide the desired vertical resolution. Nonetheless, significant increases in our capability to resolve the vertical structure of water vapor distribution are likely over the next decade and beyond (Sections 3.3 and 4.2). As an intermediate step towards a higher vertical resolution global water vapor data set, it is recommended that the feasibility of constructing a coarse vertical resolution global water vapor data set be examined.

The present NOAA operational polar-orbiting satellite sounding system (HIRS-2) contains five infrared sounding channels that are sensitive to water vapor, including the two window channels. At best, vertically integrated water vapor content can be resolved into four layers (approximately surface to 700 mb, 700 to 500 mb, 500 to 300 mb, and above 300 mb). Accuracy of the retrievals declines in the upper layers, although it should be noted that even our capacity to validate retrievals in the upper troposphere has been fairly marginal to this point. Retrievals from infrared observations are not possible when local cloud cover exceeds about 60 to 70 percent. In the near future, a 5-channel microwave radiometer (SSM/T-2) for sampling the water vapor absorption line at 183 GHz will be included on a DMSP satellite to be launched in 1991 while a nearly identical instrument (AMSU-B) will be included on NOAA-K to be launched in 1994. The spatial resolution of the SSM/T-2 and AMSU-B instruments will be about 50 and 15 km, respectively, at nadir. These microwave sensors provide coverage of cloudy areas although precipitation remains a problem as with SSM/I. The sensitivity to surface characteristics will be significantly less for some of these channels. Thus, a combination of HIRS-3 (the modified infrared sounder on NOAA-K) and AMSU-B data from the operational NOAA polar orbiters should result in a significant enhancement in our capability to resolve the vertical structure of atmospheric water vapor in the near future. Potentially, up to 5 layers could be resolved. If AMSU-B is included on both operational polar orbiters, nearly global coverage could be achieved on a daily basis. Information on the total vertically integrated water vapor (PW) derived using the lower frequency observations at 22 GHz from SSM/I may provide a useful constraint for improving the accuracy of retrievals using the infrared and higher frequency microwave channels.

Thus, it is recommended that the quality of present water vapor profile retrievals (and radiosonde observations) be definitively assessed (Section 4.5), especially with respect to resolution of the middle and upper troposphere, and that the feasibility of constructing higher vertical resolution data sets using anticipated near-term enhancements in satellite observing capability be explored. In particular, techniques using a combination of sensors (infrared and microwave) should be developed and assessed. Resolution of five layers should serve as a reasonable near-term objective; e.g.,

Surface - 850 mb

850 mb - 700 mb

700 mb - 500 mb

500 mb - 300 mb

300 mb - 100 mb

although the selection and number of layers is contingent upon our ability to retrieve meaningful information in these layers. The rationale, in part, for the selection of these layers is based on the desire to resolve the moist convective boundary layer (typically surface to 800 mb in the tropics), the boundary layer to freezing level (typically between 500 and 600 mb in the tropics), and the lower and upper portion of the upper troposphere (tropical tropopause typically near 100 mb). The boundary layer represents the dominant moisture source for deep convective systems in the tropics. Outflow from these systems occurs predominantly above the freezing level in the form of mesoscale anvils which may become self-maintained to some extent (Houze and Hobbs, 1982; Hartmann *et al.*,1984). The input of moisture into the upper troposphere via deep convection is believed to be a primary source of water vapor at these levels where the radiative effects are substantial (Section 2.1.2) and which can be rapidly transmitted to remote locations via advection in the generally stronger flow at these levels (Del Genio *et al.*, 1991).

Significant progress is needed in our ability to assimilate all types of moisture data into global analyses of the atmosphere and climate systems (Section 2.2.4). Such studies should be undertaken. In particular, efforts to produce analyses of water vapor transport through the atmosphere (e.g., Schubert and Park, 1991) are especially attractive and would serve to further assess and improve the performance of general circulation models and to significantly enhance our knowledge of the global hydrologic cycle.

Finally, it is very strongly recommended that present efforts to construct a vertically resolved (1 km) global climatology of water vapor in the upper troposphere and lower stratosphere based on solar occultation measurements from SAGE II (and the planned HALOE and SAGE III instruments) be continued. Although these observations suffer from sampling bias (as is also true of other present satellite-based techniques) and comparatively infrequent measurement opportunities (Section 3.2.4), the lack of other accurate moisture information at these climatically sensitive altitudes places a very high priority on continuing to collect and analyze these data.

4.2 High Vertical Resolution Global Satellite Observations

A complete understanding of the atmospheric hydrologic cycle must await truly global measurements of the important state variables at a vertical resolution matching GCMs of the future (20 or more levels). At a minimum, simultaneous and coincident measurements of wind, temperature, and water vapor are needed twice daily. Global coverage every 6 hours is desired.

Simultaneous observations of wind and water vapor content are needed to accurately specify surface evaporation and the quasi-horizontal transports, while coincident observations of temperature and water vapor are needed to quantify the static stability of the atmosphere that is crucially important in the development of deep convective disturbances.

Coincident profiles of wind, temperature, and water vapor are required at a horizontal resolution approaching 100 km over the globe. Even greater horizontal resolution may be required for water vapor given the high degree of variability observed at the mesoscale. Vertical resolution of 0.5 km or less is needed to resolve the planetary boundary layer and capping inversion while 1-km data may suffice for the remainder of the troposphere. The required accuracy for winds is within 1 to 2 m s^{-1} in the lower troposphere and 2 to 5 m s^{-1} aloft. Temperatures must be known to 1°C or better. Moisture values must be accurate to within 10 percent, particularly below the 700-mb level. A ±5 percent accuracy in the boundary layer is highly desirable.

The most promising method to obtain the required simultaneous high vertical resolution measurements from space is to combine a Doppler lidar wind sensor such as Lidar Atmospheric Wind Sounder (LAWS) planned for EOS (Baker, 1991), with differential absorption lidars (DIAL) designed to measure both temperature and water vapor. This unique combination of lidar technologies represents a true next generation of satellite-based atmospheric sounders. It is a radically new approach, both in terms of technology and measurement principles, that could substantially alter the nature of atmospheric sounding for the next century. The magnitude of its potential impact on our understanding of the hydrologic cycle and atmospheric general circulation and on our capabilities for numerical prediction of weather and climate leads to the conclusion that basic and applied research supporting achievement of this capability should receive high priority.

The baseline LAWS instrument will provide accurate atmospheric wind profiles at a horizontal resolution (~100 km) exceeding that presently available even over the land areas of the Northern Hemisphere where the rawinsonde (radiosondes with wind observing capability) network is most dense. The vertical resolution of LAWS wind observations (~1 km with ~0.5-km resolution in the boundary layer) will be comparable to that of rawinsonde data. Although there may be some limitations in the ability of LAWS to observe winds at levels above the middle troposphere because of the potential lack of sufficient backscattering aerosols there, measurements in the lower to middle troposphere should be reliable and of very high quality (~1 to 2 m s^{-1}). Data loss due to cloud obscuration should not be a major problem. The prevalence of optically thin high cirrus clouds in these regions may actually result in reasonably good upper tropospheric coverage by providing suitable backscattering targets. The addition of DIAL capability could provide accurate observations of atmospheric temperature (±1°C) and water vapor content (±10 percent) at a horizontal resolution comparable to that used in present models of the global atmospheric circulation (~250 km). The vertical resolution of the observations of wind and temperature will be comparable to conventional rawinsonde observations while the water vapor observations will be even more detailed. The vertical resolution will substantially exceed that achieved by present or future satellite-borne passive sounding systems, which are fundamentally limited by the vertical breadth of the weighting functions even for spectrally narrow channels (Houghton, *et al.*, 1984). Furthermore, derivation of the soundings will not depend on first-guess profiles as is the case for passive sounding (e.g., Reuter, *et al.*, 1988). The vertical resolution will be best in the lower troposphere (~0.5 km for temperature and ~0.3 km for moisture) where detailed knowledge of temperature and water vapor is crucially important to understanding convective development. Accuracy should also be best at these levels.

It must be emphasized that the vertical resolution achieved by a DIAL cannot be matched using passive sounders. Even at very high spectral resolution, the half-power vertical width of the weighting functions for individual passive sounding channels is on the order of kilometers. Consequently, as the number of passive sounding channels is increased, the amount of independent information per channel decreases because of the substantial overlap (Smith and Wolf, 1976). This leads to ill-conditioning when deriving the corresponding temperature and water vapor profiles by iterative inversion of the radiative transfer equation (Houghton, *et al.*, 1984). This problem is alleviated by externally supplying first-guess temperature and water vapor profiles. In this way, it is possible to estimate vertical structure finer than the actual vertical resolution of the sensor. However, the result depends on the information contained in the initial-guess profiles and on the use of a sophisticated algorithm for constraining the solution to preserve this vertical structure in the retrieval iteration.

The horizontal resolution achieved with passive systems, such as AIRS, will be much better than that of initial DIAL systems. However, the passive and active systems are highly complementary. Each has its own unique capabilities for advancing Earth System Science. The vertical structure and moisture information derived from a DIAL system is unique and would serve ideally as the independent first guess input to a structure-preserving inversion algorithm used for processing data from a passive sounding system with much greater horizontal resolution. The lidar soundings could be used directly, or alternatively, the output of a data assimilation system incorporating the lidar information in the analysis cycle could be used. In this way, the resulting data set might have the best characteristics of each; i.e., accuracy and detailed vertical structure along with mesoscale horizontal resolution for both temperature and water vapor. Because of the potential importance of this source of high vertical resolution global data in addressing the atmospheric component of the hydrological cycle, it is recommended that a comprehensive research program be initiated to advance the technology of DIAL systems so that they can be deployed effectively from a space platform in the EOS time frame.

Among the various active optical methods that have been developed during the past 20 years, DIAL is the most widely used for the measurements of minor constituents in the troposphere and stratosphere. The DIAL technique has now reached a high degree of maturity in both its methodological and technical aspects. Detailed studies of this technique for space applications were published as early as 1979 (Shuttle Atmospheric Lidar) and the results of DIAL measurements using ground-based, mobile, and airborne systems have strengthened the confidence in the potential of a spaceborne system (Browell, *et al.*, 1979; Kalshoven, *et al.*, 1981; Cahen, *et al.*, 1982; Korb, *et al.*, 1985; Ismail and Browell, 1989).

The most critical technology requiring further development is the laser transmitter. Space-based lasers used for DIAL need to be accurately tunable, need to hold the tuned absorption wavelength, and must be small, lightweight and energy efficient. These characteristics can be attained with continued focused development. Other areas needing improved technology include tunable optical filters, advanced photo-detectors and narrow field-of-view scanning telescopes. The improvement in our knowledge of the global hydrological cycle resulting from a space-borne lidar system will make this technology development effort well worth the effort.

4.3 Improved Parameterization of Moist Processes

4.3.1 Intensive Field Observation Campaigns

Intensive field campaigns are needed to enhance our basic knowledge of the role of water vapor in various key hydrologic processes and to provide bases for the improvement of GCM parameterizations (Section 2.2.3). An essential requirement for such field campaigns is that they provide comprehensive observations over multiple scales. At a minimum, the observations should be sufficient to define the average conditions within an area corresponding to the size of a typical GCM grid box. High spatial and temporal resolution must also be provided within that area in order to resolve the physical processes that occur. Moreover, the observations must include all the relevant parameters required to adequately define the phenomena of interest. For example, observations of wind and temperature structure, cloud properties and precipitation would be needed for an experiment focused on cloud formation.

It is also absolutely essential that observational and analysis activities be strongly coupled and complementary to an active modeling effort designed to advance our fundamental understanding of the physical processes. The mutual interaction between these components is key to optimizing experimental design and realizing the basic objectives of increased understanding and improved theories, models and parameterizations.

Specific candidate hydrologic processes of high interest include:

- evaporation over tropical and cold ocean surfaces;
- evaporation and evapotranspiration over a variety of land surfaces;
- boundary-layer transport processes in a variety of situations;
- formation of extended boundary-layer clouds including marine and continental cumulus, stratus and stratocumulus;
- formation of extended cirrus cloud systems in tropical, subtropical and midlatitude locations;
- deep precipitating convective cloud systems in tropical, subtropical (monsoon) and midlatitude environments; and
- extratropical cyclones and frontal systems.

Ongoing or planned research programs currently exist that are focused on one or more of most of these processes, as described in Section 5. *Addition or enhancement of a strong focus on water vapor observations to these programs/ experiments will clearly add to their value and be mutually beneficial.* What is needed is as complete a characterization as possible of these hydrologic processes including accurate descriptions of the distribution of atmospheric water vapor. It is therefore recommended that efforts be made to improve and enhance water vapor measurement capabilities for these types of activities.

4.3.2 Longer Duration Intensive Climatological Observations

Acquisition of data sets of sufficient duration and resolution to begin to address basic questions about the structure, variability and transport of water vapor in the lower and, especially, the middle and upper troposphere are recommended. Initially, these data should be obtained on a near-continuous basis over periods of about 3 months at a few selected locations of climatological importance. The longer duration (compared to intensive field deployments) and consistent sampling at each location will ensure that the data and analyses are climatologically and statistically significant. Temporal resolution should be adequate to resolve mesoscale features and discontinuities that appear prevalent in cloud fields and likely represent fundamental scales of organization in the dynamical and moisture fields. Vertical resolution should be capable of defining the laminated structure of water vapor that is observed in high-resolution data.

A surface-based Raman lidar system (Section 3.4.3) capable of sensing the lower, middle and upper troposphere would most ideally serve as the primary water vapor observing system meeting the requirements for sampling frequency, vertical resolution and vertical coverage. Further development of this technology will be required to achieve coverage of the upper troposphere, especially for daytime observations. A second key system that would greatly enhance the scientific value of the observations is a surface-based radar wind profiling system (400 and/or 50 MHz). Addition of a radio-acoustic sounding system (RASS) capability to the wind profilers would provide useful data on lower troposphere thermal structure. These data should be obtained on a near-continuous basis at the same location with temporal and vertical resolution comparable to that of the water vapor profiles. In combination, these data will permit evaluation of the horizontal transports, estimation of the vertical transports, and an assessment of the dynamic origin of water vapor structure and variability.

In addition, coincident rawinsonde data should also be taken on a regular schedule using sondes with both state-of-the-art and conventional humidity sensors, and temperature and wind-finding systems. The frequency of balloon soundings should be enhanced with respect to the usual synoptic schedule. These data will serve to better establish the thermodynamic origins of water vapor structure and variability, facilitate analyses in terms of relative humidity, as well as provide a basis for assessing the errors and biases inherent in previous and present global analyses derived from conventional synoptic observations.

Coincident data from geosynchronous and polar orbiting operational satellites (GOES and NOAA), especially from sounding instruments (VAS and HIRS-2/ MSU), should also be acquired over a region surrounding the surface observing sites. These data will enable evaluation, and potentially improvement, of present (and future) satellite-based water vapor sounding algorithms, provide a means to monitor the radiative impact of atmospheric water vapor on the earth-atmosphere system, and permit assessment of the relationship between cloudiness and the water vapor and dynamic fields.

Lastly, the downwelling and upwelling broadband radiative fluxes (infrared, near infrared, and visible) at the surface should also be measured to quantify the radiative impact of atmospheric water vapor and associated clouds on the surface and atmosphere. More detailed spectral radiance measurements would provide additional useful information.

Prospective climatologically sensitive locations at which to conduct extended time observations include:

1) a tropical location for low- and middle-level water vapor associated with inflow to tropical convective systems;

2) a subtropical location for middle and upper tropospheric water vapor associated with large-scale circulations (the Hadley cell and subtropical jet stream) incorporating the outflow from tropical convection disturbances;

3) a subtropical/midlatitude location for water vapor associated with the interaction of synoptic-scale flows of tropical and midlatitude origin;

4) a midlatitude location for lower, middle and upper level water vapor associated with summertime mesoscale convective disturbances and synoptic-scale extratropical cyclones in the winter season.

4.4 Basic Research on the Role of Water Vapor and its Variability

Increased emphasis on basic research on the role of water vapor and its variability in meteorological, hydrological and climatological processes is sorely needed. Such activities include technology development and utilization; development and evaluation of algorithms for application to satellite data; and development and/or improvement and validation of models of various hydrologic processes and models of the global hydrologic and climate systems, as described elsewhere in Section 4. High-priority basic research activities also include:

- Analysis of water vapor observations in relationship to pertinent meteorological or other parameters, especially with respect to quantifying the fundamental characteristics and origins of water vapor variability and its role in hydrologic processes in the climate system.

- Experiments with detailed models of various hydrologic processes to: 1) increase basic understanding of these processes, 2) quantitatively assess the role of water vapor in these processes, and 3) provide guidance for the design of observational activities and for the analysis of data obtained.

- Four-dimensional data assimilation (FDDA) studies designed to: 1) improve our knowledge of the atmospheric hydrologic cycle and 2) quantify the sensitivity of global, model-based analyses to improvements in the assimilation of water vapor observations and the parametric representation of physical processes.

- GCM experiments designed to: 1) increase basic understanding of the global hydrologic cycle and climate system, including the land surface (biosphere and cryosphere) and ocean components; 2) quantify the sensitivity to improvements in treatment of resolved transport processes; 3) quantify the sensitivity to improvements in parameterizations of unresolved physical processes; and 4) support global analysis efforts and efforts to develop improved future global observing capabilities.

Lastly, an activity fundamental to the success of GVaP is research directed at evaluating and improving our basic capability to accurately observe atmospheric water vapor. This is described below.

4.5 Measurement Intercomparisons: An Essential Activity

The appreciable uncertainties in our knowledge of the errors associated with present satellite-based and conventional (radiosonde) global water vapor observing systems are clearly not acceptable (Section 3). Attempts to utilize these observations will continue to suffer from these uncertainties and seriously retard progress in understanding hydrologic and atmospheric processes on all scales. In particular, the actual error characteristics and their systematic and/or random components must be quantified and understood. New water vapor observing capabilities have been developed in the research environment, including active and passive remote sensing capabilities as well as improved techniques for making *in-situ* observations from balloons and aircraft (Section 3). Even here, however, much uncertainty exists with respect to the actual absolute accuracy and quality of these data. Improved knowledge of their error characteristics is also essential. Fundamentally, a useful absolute "ground truth" measurement of atmospheric water vapor is not presently available or, at the least, has not been established as such. Much of the uncertainty in the quality of present and future water vapor retrievals from satellite observations derives from this fact.

Rigorous intercomparison efforts involving the entire range of present and developmental water vapor observing capabilities are needed to achieve the objectives of GVaP. This would include an evaluation of accuracy, precision, response time, vertical resolution, etc., of as many devices as possible and should be accomplished at a common site. The latter should be selected to coincide with one or more of the intensive field experiments described earlier (Section 4.3.1) in order to exploit the advantages of additional measurements, particularly the field of motion. Some independent intercomparison field activities may also be required.

Such intercomparison experiments should seek to develop a full characterization of each of the various sensing systems. Moreover, there must also be a very strong focus on the quantitative evaluation of water vapor measurements deduced from various satellites and from radiosonde observations since these are key to our understanding of the global hydrologic cycle. The results of these activities should help provide the basis for an informed choice of particular systems, analysis techniques, or algorithms to best meet specific observational requirements dictated by the scientific objectives.

5. Major Field Efforts Underway

Improved observations of atmospheric water vapor could contribute very substantially to several major research programs of the World Climate Research Program (WCRP), including: the World Ocean Circulation Experiment (WOCE), the Research Programme on Interannual Variability of the Tropical Ocean and Global Atmosphere (TOGA) and its Coupled Ocean-Atmosphere Response Experiment (COARE), the International Satellite Cloud Climatology Project (ISCCP) and its First ISCCP Regional Experiment (FIRE), and the Hydrological-Atmospheric Pilot Experiment (HAPEX) and the International Satellite Land Surface Climatology Project (ISLSCP) and their various field experiments. Improved water vapor observations could also contribute substantially to national programs such as the Storm-scale Operational and Research Meteorology (STORM) program and its planned Winter and Summer Phase Field Experiments and the Atmospheric Research Measurements (ARM) program of the Department of Energy. GVaP will promote understanding of the various components of the hydrologic cycle, that are individually addressed by these programs. In concert with these programs, GVaP will also promote understanding of the *entire* water cycle by providing the means to better describe interactions between the various components and thereby facilitating synthesis of the results of these individual programs.

5.1 WOCE, TOGA, and TOGA/COARE

The goal of WOCE is to describe and understand the ocean circulation and its relationship to climate change over periods of decades and longer. During the 1990s, WOCE will undertake an unprecedented program of world-wide ocean observations and measurements, with the aim of improving both the description of the ocean and the models to be used for climate prediction.

TOGA is very closely related to WOCE. Its objectives are to improve the description of the tropical oceans and the global atmosphere as a time-dependent system, to study the feasibility of modeling and predicting the coupled ocean-atmosphere system, and to provide the scientific background for designing an observing system for operational prediction--if this capability is demonstrated by coupled models.

Both TOGA and WOCE require accurate determinations of the air-sea exchanges that contribute to the formation and modification of water and air masses, drive oceanic circulation, and form the ocean-atmosphere linkages that ultimately affect climate. These include the momentum flux, the sensible and latent heat flux and the freshwater (precipitation) flux. Knowledge of the near-surface atmospheric humidity is needed for the calculation of the latent heat flux and the freshwater flux.

Spot estimates of the air-sea fluxes may be obtained from either *in-situ* or satellite observations or from four-dimensional data assimilation as a by-product of the calculations of atmospheric general circulation models. Early in the planning of WOCE, it was concluded that neither *in-situ* observations nor satellite observations by themselves would be sufficient to provide the global surface fluxes needed to drive ocean models and that data assimilation using atmospheric models offered the best approach to provide the needed fluxes. The atmospheric models and complex analysis methodology that comprise four-dimensional assimilation systems offer an effective way to quality control and blend the available *in-situ* and satellite observations and to fill in data gaps through the model dynamics. However, recent comparisons of surface atmospheric fields and fluxes from a number of models with *in-situ* observations indicate that current model fluxes will not be adequate to meet the accuracies required for air-sea interaction studies. Both WOCE and TOGA are conducting major research efforts to improve the air-sea flux estimates to be obtained from four-dimensional data assimilation, including an intensive field experiment (TOGA/ COARE) in the western Pacific (WCRP, 1990a) in 1992-1993.

Improved measurements of near surface water vapor, in addition to other *in-situ* and space-based observations, could contribute to improving calculated air-sea fluxes by providing improved initial condition and verification data sets for the models and, even more importantly, by contributing to the improvement of the model flux parameterizations. This is particularly true for lidar measurements, where the evolution of water vapor in the planetary boundary layer can be observed nearly continuously in time and compared to the evolving moisture patterns predicted by the models used in data assimilation.

5.2 ISCCP and FIRE

Both ISCCP and FIRE are concerned with evaluating and improving algorithms for the retrieval of cloudiness from satellite observations. ISCCP aims to develop a global climatology of various cloud types and will contribute global cloud statistics (Schiffer and Rossow, 1983). Its main emphasis is directed toward the evaluation of overall GCM performance in predicting cloudiness parameters. FIRE, on the other hand, is directed towards improving parameterizations of cloudiness and radiation algorithms in GCMs (Cox *et al.*, 1987). FIRE aims to describe the mesoscale features and lifetimes associated with cloud populations over a region and attempts, through intensive field measurements and coordinated modeling activities, to contribute to the understanding of processes giving rise to them (Starr, 1987).

FIRE utilizes ground-based, airborne and satellite observations. The ground-based and airborne observations provide independent observations of cloudiness parameters such as cloud height and cloud amount, which can be compared both to the ISCCP product (Rossow and Schiffer, 1991) and to other satellite-derived estimates for those locations and times. They will also contribute information on parameters such as cloud base height which are important for GCM model parameterizations but can be obtained from satellite observations only with great difficulty--if at all.

Airborne and ground-based observations, as well as balloon soundings and satellite observations, provide the sort of comprehensive, multiparameter and multiscale description of clouds and their environment required to resolve the processes contributing to cloud formation and maintenance and which determine the physical properties of the clouds. Accurate and reliable water vapor observations are crucial to the full understanding of cloud formation, development and decay.

Two intensive field campaigns of FIRE have already been completed. One focused on cirrus clouds conducted over Wisconsin (Starr and Wylie, 1990) and the other focused on marine stratocumulus clouds conducted over San Nicolas Island off the coast of Southern California (Albrecht *et al.*, 1988). A second cirrus campaign is scheduled for November 1991 over Coffeyville, Kansas addressing different aspects of the cirrus problem while a second marine boundary layer campaign is planned for 1992 near the Azores (ASTEX).

5.3 ISLSCP and HAPEX

ISLSCP and HAPEX are international programs designed to increase understanding of land surface processes including, in particular, biospheric, geochemical and hydrologic processes and their interactions with the atmosphere. A major objective is to develop methodologies for deriving quantitative information concerning land surface parameters from satellite observations of the radiation reflected and emitted by the Earth as well as providing detailed data sets for use in describing land surface processes. Such quantitative information is required to:

1. monitor global scale changes of the land surface caused by climatic fluctuations or by the activities of man;

2. further develop mathematical models designed to predict or simulate climate on various time and space scales; and

3. permit inclusion of land surface climatological variables in diagnostic and empirical studies of climate variation.

It is well known that climate fluctuations and trends may have effects on society on a regional as well as global scale. Land observations from satellites will become part of a data base for monitoring changes of the surface. A major application of the data from ISLSCP then is global and regional monitoring of such changes.

The First ISLSCP Field Experiment (FIFE), conducted in 1987 over the Konza Prairie in Kansas (Sellers *et al.*, 1988), and the HAPEX Modélisation du Bilan Hydrique (MOBILHY), conducted in southwestern France in 1985-1987 (André *et al.*, 1988), were designed to obtain the relevant satellite and ground truth data for validation of algorithms relating land surface parameters to satellite radiances and to provide detailed data sets to further understand land surface processes. These activities are continuing with a number of field experiments planned over the next decade and focused on various surface types (WCRP, 1990c). The results of these experiments will enable us to improve our interpretive techniques and place greater confidence in the precision and validity of satellite-derived quantities which will ultimately allow us to assemble truly global data sets of those parameters associated with land surface climatology. A main focus is to validate satellite-inferred properties related to the physics of surface atmosphere interactions. Clearly important interactions include heat, momentum, moisture, and radiation fluxes.

Water vapor measurements, especially close to the surface and of high temporal resolution, are needed to improve our understanding of evaporation and evapotranspiration. These observations must also extend at least to the top of the PBL and over the spatial extent of the field sites so as to assess the integrated effect of various land/vegetation subtypes. Knowledge of surface moisture flux over land surfaces must be improved if we hope to address the hydrological cycle.

5.4 STORM

The goals of STORM are to improve the short-range prediction of precipitation and severe weather events, and to advance the fundamental understanding of precipitation and other mesoscale meteorological processes. Of particular interest is the role of scale interactions in producing mesoscale weather systems and the impact of such systems on larger scales. STORM will address the spatial variability of precipitation and other components of the hydrologic cycle in association with mesoscale convective systems and winter storms. STORM is uniquely designed to encompass the entire range of scales relevant to mesoscale convective systems, which are the primary source of precipitation in the central United States during the spring and summer seasons.

STORM will conduct several intensive field experiments during the 1990s (NCAR, 1989). The multiscale observing networks will cover an area much larger than in any previous experiment designed for remote sensing validation. In addition to the new operational observing systems which comprise the NWS modernization effort (~80 NEXRAD Doppler radars, ~30 radar wind profilers at separations of between 200 and 400 km, the automated surface observing system - ASOS, and GOES-Next), these field experiments will employ a wide range of research systems, which according to the experimental design include:

- 7-9 additional ground-based Doppler radars,
- more than 10 research aircraft, including 4 with Doppler radar,
- ~45 CLASS rawinsonde sites,
- more than 5 radio acoustic sounding systems (RASS)--temperature observations in lowest 2 km,
- microwave radiometers--integrated water vapor and cloud liquid water,

- more than 150 mesonet surface sites,
- several boundary-layer instrumentation systems (BLIS)--a tethered balloon sounding system.

Three nested observing networks are planned with average sensor separations of about 400 km, 250 km, and less than 50 km. Examination of the instrumentation list shows that the water vapor measurements are inadequate in comparison to capabilities for observing the mass and momentum fields at various scales. The NWS and CLASS rawinsonde observations are being relied upon to provide water vapor information at the larger scales (alpha and beta) with supplementary data provided by research aircraft , satellite estimates, and an unknown number of surface-based microwave radiometers and infrared radiometers. At the finest resolved scale (gamma), more detailed information will be available from various observing systems including tethered balloons. However, information on water vapor distribution will probably also be inadequate at this scale. Just as in TOGA/COARE, four-dimensional data assimilation is integral to the approach for STORM. Nested regional-scale assimilation models will be used to blend various kinds of data in a consistent manner. STORM provides a unique opportunity to collect and analyze data in a manner consistent with resolving important hydrologic processes over a range of scales compatible with application to parameterization issues.

5.5 ARM

A principal objective of the Atmospheric Radiation Measurement (ARM) program of the U.S. Department of Energy is to provide an improved understanding of radiation transfer in the atmosphere (DOE, 1990). With CO_2 continuing to increase in the Earth's atmosphere it is expected that surface temperatures will rise due to the greenhouse effect. Most global climate models indicate that taken alone, a doubling of CO_2 will likely only increase the surface temperatures by a few tenths of a degree averaged globally. However, this relatively small change is expected to trigger other phenomena such as increased moisture and changes in clouds and surface albedo leading to an overall increase in temperature by several degrees. With this prospect in mind, the ARM program has been designed to acquire a long-term data set of radiation parameters and other important measurements at selected sites around the world.

Since water vapor is the most active greenhouse gas in the atmosphere, careful and accurate water vapor measurements are needed as part of ARM. Profiles of water vapor with good vertical resolution and vertical coverage are needed to fully understand the impact of moisture on radiative transfer. Coverage of the upper troposphere is particularly important because a water vapor molecule in the upper troposphere may be as much as 100 to 1,000 times more effective in trapping infrared radiation than a water vapor molecule in the boundary layer.

6. Project and Data Management

GVaP is proposed as an initiative for the GEWEX program. It is anticipated that GVaP will be managed by an international Science Steering Group (SSG) supported by the International GEWEX Project Office (IGPO) and reporting to the WCRP Joint Scientific Committee Scientific Steering Group for GEWEX. The strategic plan contained in this document was developed at a workshop entitled "The Role of Water Vapor in Climate Processes" held at Easton, Maryland from October 30 to November 1, 1990. A list of attendees is included in the Appendix. This plan was presented to the GEWEX Scientific Steering Group in Bermuda on January 21-25, 1991.

6.1 Project Management

The GVaP SSG, made up of active scientists interested in accomplishing the overall goal of GVaP, is charged with the responsibility to coordinate the research efforts outlined in Section 4. The strategic research plan spells out the importance of improved water vapor observations at all scales along with the need to improve atmospheric models to incorporate better observations. Coordination of these activities along with the need to structure our field activity within other ongoing field programs provides the real challenge for the SSG.

The SsG is to develop an implementation plan which describes the priority and details of the various research elements, and orders the activities so as to allow for their completion in a timely fashion taking into consideration various constraints. The implementation plan is expected to be finalized by December 1991. During the life of the project, the SSG will provide leadership and scientific advice on the conduct of the various research endeavors, and will be responsible to encourage early and collaborative publication of all scientific findings.

6.2 Data Management

A data management plan is essential to provide a timely, complete and accessible set of data to support the scientific objectives of GVaP. A variety of data is to be acquired during GVaP from a number of different observational systems. The data sets must serve the needs of the scientific community in order to meet the specific objectives of GVaP. Therefore, for these data to be useful and timely, an organized activity should be initiated for processing and archiving of the data. The data should be put into standard geophysical format for archiving at the World Data Centers and for disseminating the data to the user community. In addition, GVaP scientists must be assured of access to real-time and/or near-real-time data in the most expeditious manner possible. A detailed data plan should be developed as an important part of the GVaP implementation plan. General guidelines for the data plan are that:

1. Investigators provide their data to scientific users in a uniform and well-documented format within a time frame appropriate to use of the data.
2. Quality control flags be provided with data so that researchers can appraise the utility of observations or derived quantities.
3. Raw data be preserved so that it can be reprocessed in case of changes in algorithms or parameters.
4. Standard data products be established in close collaboration with data managers and scientific users.
5. Flexibility be maintained in the data management system to account for evolving science while assuring a consistent data set.
6. Relevant data from other collaborative research activities of interest to GVaP be collected and archived.

7.0 Summary Conclusions

Throughout this strategic plan there are important recommendations leading to an improvement in our understanding of the role atmospheric water vapor plays in climate processes. The major recommendations are summarized here.

- Initiate a program to establish an atmospheric water vapor climatology on all scales.
- Support research and development to improve water vapor measurement technology both remote and *in-situ* from surface, aircraft and spacecraft platforms.
- Improve the existing global upper air sounding network so that it provides consistent, high-quality water vapor profiles.
- Conduct intensive and longer term observational field programs designed to improve knowledge of water vapor distribution and its role in moist processes.
- Continue to develop and improve hydrologic process models in conjunction with the recommended observational activities.
- Continue to develop, test, and improve treatment of moist processes within global climate models and global data assimilation models, including processes that are explicitly resolved and those that must be parameterized.
- Promote wide distribution of water vapor data sets.

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ROLE OF WATER VAPOR IN CLIMATE PROCESSES WORKSHOP ATTENDEES

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16. Abstract

The proposed GEWEX Water Vapor Project (GVaP) addresses fundamental deficiencies in the present understanding of moist atmospheric processes and the role of water vapor in the global hydrologic cycle and climate. Inadquate knowledge of the distribution of atmospheric water vapor and its transport is a major impediment to progress in achieving a fuller understanding of various hydrologic processes and a capability for reliable assessment of potential climatic change on global and regional scales. GVaP will promote significant improvements in knowledge of atmospheric water vapor and moist processes as well as in present capabilities to model these processes on global and regional scales. GVaP complements a number of ongoing and planned programs focused on various aspects of the hydrologic cycle including: HAPEX and ISLSCP and their various field campaigns for surface fluxes over land, WOCE and TOGA/COARE for air-sea interaction, ISCCP and FIRE for clouds and cloud formation, and GPCP, STORM and TRMM for precipitation. The goal of GVaP is to improve understanding of the role of water vapor in meteorological, hydrological, and climatological processes through improved knowledge of water vapor and its variability on all scales. The document provides a detailed description of the GVaP.

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