The cover picture shows a pair of radar images taken at ROHK at 1051 and 1209 HKT on 16 June 1993 during the heavy rainstorm that day. Such intense convective storms occur often in Hong Kong posing a hazard to the territory. In this issue a paper by Mickey M.-K. Wai, Patrick Welsh and Wai-Man Ma investigates the factors which affect the timing and the distribution of summer convective rainfall over Hong Kong and South China.

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Editorial

This issue of the Bulletin contains two papers concerned with analysis of two important features of the seasonal climatology of Hong Kong and southern China. One relates to summer non-tropical cyclone rainfall, its association, timing and distribution. The other paper deals with the prediction of northerly cold surges arriving in southern China.

The first paper, by Mickey M.-K. Wai of the Department of Meteorology, Florida State University, Tallahassee, Florida, Patrick T. Welsh of the U.S. National Weather Service, Jacksonville, Florida and Wai-Man Ma of the Royal Observatory Hong Kong, examines the local mechanisms affecting the timing and distribution of summer convective rainfall over Hong Kong. This is achieved by linear analysis of dynamic and thermodynamic equations which indicate that local circulations are associated with features, the primary forcing mechanisms of which are surface heating, surface cooling and terrain.

In the second paper, Y.C. Cheng, W.K. Wong and K. Young of the Department of Physics, The Chinese University of Hong Kong, M. Zhang of the Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China and C.Y. Lam and H.T. Poon of the Royal Observatory Hong Kong, present Froude Number statistics for northerly surges invading the coast of southern China and Hong Kong with the aim of developing a reliable predictor for the arrival of cold surges passing over the Nanling Range. Their conclusion is that unambiguous predictions can be obtained for the arrival of northerly cold surges using a forecasting index pair developed from such statistics.

As in the previous issue the latest issue, Issue 9, of The United Nations Climate Change Bulletin has been included. This provides articles and information of a general nature concerning the subject of climate change which may be of interest to readers.

The remainder of the Bulletin contains the regular features News and Announcements, Hong Kong Weather Reviews, Meeting Reviews and the Calendar of Coming Events. The News and Announcements section contains much useful information including the verifications of the 1995 Atlantic Hurricane Season Activity and Sahel Rainfall forecasts made by Colorado State University meteorologists included in Bulletin 5(I). In addition there are also extended range forecasts for 1996 for these two items as well as an extended range prediction of ENSO conditions from the same institution. There is also a preliminary summary of 1995 tropical cyclones affecting Hong Kong and information on the availability of meteorological data and software.

The Editorial Board expresses their thanks to the contributors. As always we hope that readers will find this issue useful and informative. All comments and suggestions for items to be included as well as news and contributions of articles related to your own activities are always welcome.

Bill Kyle, Editor-in-chief

HKMetS BULLETIN Vol. 5, No. 2, 1995
Mickey M.-K. Wai 1, Patrick T. Welsh 2 and Wai-Man Ma 3

1 Department of Meteorology, Florida State University, Tallahassee, FL
2 National Weather Service, Jacksonville FL and
3 Royal Observatory, Hong Kong

The Timing and Distribution of Summer Convective Rainfall over Hong Kong and South China

ABSTRACT

The climatic rainfall patterns on regional and local scales in South China indicate that the summer non-tropical cyclone rainfall is associated with localized convective storms. The frequency of these storms shows a high percentage of occurrence near day break or at midday. The development of these storms requires local circulations as initiating mechanisms.

The linear analyses of dynamic and thermodynamic equations indicate that local circulations are associated with the downslope wind, the upslope wind and the sea-land breeze. These surface winds constitute the secondary circulation over Hong Kong. The primary forcing mechanisms are surface heating, surface cooling and terrain.

When the downslope wind/land breeze converge with the monsoonal flow, the low level convergence of flows will initiate convection. Similarly, the upslope wind and the sea breeze readily lift warm, moist air to saturation and produce heavy rainfall. The blocking effect and deflection of the low level stratified wind can also trigger deep convection upstream or in the areas adjacent to the mountain range.

1. Introduction

Since observations began in January 1884, numerous severe storms during the monsoonal season have triggered flash floods and land slides which inflicted damage in property, infrastructure, crops, and lost human lives (Lam, 1993; Lee, 1983 a,b; Chen and Yerg, 1979; Chan 1976, Chen, 1969). To gain insight into the storm environment, the staff at the Royal Observatory (RO) have re-analyzed the synoptic-scale kinematic fields of several severe storms that affected Hong Kong since 1969. The results of the re-analysis of these storms led to recognition of basic storm environments and types. Furthermore, recent advance in remote sensing from satellite and meteorological radar along with a dense network of raingauges and high speed data processing have enabled the forecasters to detect the early development of torrential rainfall. Detailed behavior of localized heavy rainfall and its forcing mechanisms are not yet fully understood because heavy rainfall is associated with release of convective instability concentrated on a small space scale and short time scale. To improve and provide consistent forecasts of the storm, the staff at the Royal Observatory has also implemented high resolution numerical weather forecasting models (Chan, 1989), and a mesoscale numerical model (Yeung et al., 1989). A case study of the May 1992 storm using the RO limited area model with horizontal resolution of 1 degree, Shun (1992) found that the timing of the peak rainfall was off by 12 hours. Furthermore, the models could not reproduce the observed rainfall patterns. Accurate medium range forecasting for Hong Kong with numerical weather prediction models remains a difficult problem because of our limited ability to model precipitation processes (Wai and Krishnamurti, 1992), and the constraints on horizontal resolution (Simmons and Dent, 1989), initial conditions (Krishnamurti et al., 1990) and boundary conditions (Anthes et al., 1989). Therefore, there are constant reminders in small scale storm forecasting that our current knowledge of local storm developments needs improvement. A better understanding of the triggering mechanisms of the storm, the rainfall distribution, and the storm dynamics will eventually help to improve forecaster’s skill and the formulation of the numerical forecasting model.
2. Knowledge of the Summer Storms in South China

a. Existing regional rainfall patterns in South China

The regional rainfall pattern in South China provides a clear indication of the mesoscale influences. To help in understanding the mesoscale variability in the rainfall, we highlight the physical characteristics of South China in Appendix I.

We based the analysis of the regional rainfall distribution on the climatic rainfall records. The quality of the rainfall datasets is discussed in Appendix II. From west to east, the stations are Zhanjiang (ZHJ), Yangjiang (YAJ), Macau (MAC), Royal Observatory (RO), Haifen-Shanwei (HAS), and ShanTou (SHT). From north to south, the stations are Shaoguan (SHA), Heyuan (HEY), GuangZhou (GUZ), Shenzhen (SHZ), and Waglan Island (WGL). Five of these stations (GUZ, SHZ, MAC, RO, and WGL) are located in the Pearl River delta. Station SHA is located among the Nanling system while station HEY is located in the Luofu Shan.
In Figures 2 and 3, we show three types ($R_M$, $R_m$, $R_r$) of monthly mean rainfall which are averaged over two different lengths of rainfall record. $R_M$ (solid lines) are averaged over the complete rainfall record ended at 1988 (ZHJ, YAJ, HAS, SHA, HEY, and SHZ) and at 1993 (MAC, RO, GUZ and SHT). $R_m$ (dotted lines) are averaged over a shorter rainfall record ended at 1970 for all stations. Similar to $R_M$, $R_m$ (dashed lines) are the monthly mean tropical cyclone rainfall at MAC, RO, and WGL, which are averaged over the rainfall records ended at 1970 (after Kwong, 1974).

Within Guangdong province, the distributions of both $R_M$ and $R_m$ show very similar interesting features in temporal and spatial rainfall patterns. Small differences in the values of $R_M$ and $R_m$ during the cool season indicate a small interannual variability. During the summer season, the differences between $R_M$ and $R_m$ are large, indicating a greater interannual variability, which can be related to the anomaly of the monsoonal circulation (Chen et al., 1994) and local effects.

A strong spatial variation in the summer rainfall distribution is found in the Guangdong province. The Pearl River delta region receives the maximum summer rainfall. The RO records indicate a mean rainfall of 1712 mm from May to
September, yet moving horizontally away from the delta, the rainfall amounts decrease. Within the same period, the stations ZHJ and SHT receive a mean rainfall amount of 1046 and 1078 mm respectively. Similarly, stations SHA and WGL receive a mean rainfall amount of 862 and 989 mm respectively. This areal pattern is a strong signal of a consistent mesoscale rain producing mechanism.

All coastal stations show a peak monthly rainfall exceeding 200 mm in June, indicating the character of strong early summer precipitation. Most stations also show a second, smaller peak in August. This variation of rainfall is attributed to the changes in the regional atmospheric circulation. In May and early June, the strong subtropical High in the Western Pacific near 18°N often forces tropical cyclones to re-curve before reaching the China Sea. Therefore, early summer precipitation is more likely associated with convective rainfall under the influence of the monsoonal flow.

A period of low rainfall (dry spell) occurs in the mid-summer in South China (Ramage, 1951; Ramage, 1952a; Cheng, 1978) when the subtropical High in the Western Pacific advances to 20-25°N in mid-June, and monsoonal flow penetrates deep into China near the Yangtze valley, where a period of heavy *Plum Rain* occurs (Tao and Chen, 1987). With the northward migration of the subtropical High to higher latitude in mid-July, the tropical cyclones now travel to the China coast and often bring heavy rainfall.

**Figure 3** Same as Figure 2 excepted for the meridional variation of rainfall rates. From top to bottom, the stations are arranged from north to south.
b. Tropical cyclone rainfall in South China

The typhoon rainfall was once thought to represent 50% or more of the annual rainfall in South China (Domros and Peng, 1988). Several quantitative estimates in the tropical cyclone rainfall are rather incoherent; the estimates range from 30-35% in South China (Lu, 1944), 21% at station GUZ (Chang, 1958), to 24% at station RO (Watts, 1969). Using a more stringent definition of the tropical cyclone rainfall, Kwong (1974) estimated that the mean annual tropical cyclone rainfall accounted for 20.6%, 26%, and 21.9% of the mean annual rainfall amount at stations MAC, RO and WGL respectively (Figure 2). From these studies, we assume that the non-tropical cyclone rainfall would contribute a maximum of 74% to the mean annual rainfall in Lingnan.

The diurnal cycle of non-tropical cyclone rainfall peaks near 0500 h and 1200 h. Ramage (1952b) and Peterson (1980) also noted the rainfall maximum near daybreak. Especially in early summer, some of these storms are of record intensity, indicative of storms which achieve mesoscale organization and develop into long-lived and violent convection.

c. Local rainfall pattern in Hong Kong

Within the framework of the non-tropical cyclone rainfall, we briefly discuss the rainfall patterns on the local scale. In Figure 4, we show some details of nine severe storm events as shown by the hourly rainfall at the Royal Observatory. The 24-hour rainfall amount prior to the development of the storms is also included in these figures. Some aspects of the nine storms are summarized in Table 1 and Appendix II.
All nine cases of storms occurred either in early summer (May and June) or in late summer (August) coinciding with the monthly rainfall maxima. The average storm duration is about 6 hours. The combination of consecutive storms in RS82 and RS72 lengthened the duration of the severe storm event to more than 2 days. Notably, a mesoscale organized convective event may cause storms of several-hours duration. Severe storms beyond several hours to 1 day duration are usually maintained by synoptic systems such as upper low pressure systems or trough. Extremely long-lasting severe storms (on the order of days) are related to more persistent anomalies of the atmospheric circulation.

Table 1 is a summary of the peak and accumulated rainfall rates of the nine storm events. In terms of the diurnal variation, five storms (RS92, RS83, RS72, RS66, RS889) had peak rainfall which occurred near 0600 h while five storms (RS93, RS89, RS82, RS72, and RS69) had maximum rain near mid-day. Only two storms had peak rainfall during the night or during the evening. The occurrence of these storms is similar to the climatic distribution of non-tropical cyclone rainfall.

The accumulated rainfall patterns from RS93 (Song, 1994), RS92 (Lam, 1993), RS83 (Lee, 1983a), RS82 (Lee, 1983b), RS72 (Cheng and Yerg, 1979), and RS66 (Chen, 1969) showed localized heavy rainfall in the Pearl River delta. The maximum was located in the vicinity of Hong Kong indicating local rain producing mechanism.
Table 1. Rainfall rates of nine heavy rainfall events recorded at the Royal Observatory.

<table>
<thead>
<tr>
<th>Heavy Rainfall Events</th>
<th>Peak Hourly Rainfall (mm)</th>
<th>Accumulated Rainfall (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>16/6/1993</td>
<td>55.2</td>
<td>153.0</td>
</tr>
<tr>
<td>8/5/1992</td>
<td>109.3</td>
<td>324.1</td>
</tr>
<tr>
<td>2/5/1989</td>
<td>104.8</td>
<td>208.4</td>
</tr>
<tr>
<td>17/6/1983</td>
<td>69.4</td>
<td>346.7</td>
</tr>
<tr>
<td>28/5/1982</td>
<td>29.7</td>
<td>179.0</td>
</tr>
<tr>
<td>29/5/1982</td>
<td>43.9</td>
<td>258.4</td>
</tr>
<tr>
<td>30/5/1982</td>
<td>2.9</td>
<td>11.6</td>
</tr>
<tr>
<td>31/5/1982</td>
<td>36.0</td>
<td>205.5</td>
</tr>
<tr>
<td>16/6/1972</td>
<td>34.4</td>
<td>205.9</td>
</tr>
<tr>
<td>17/6/1972</td>
<td>34.5</td>
<td>213.8</td>
</tr>
<tr>
<td>18/6/1972</td>
<td>98.7</td>
<td>232.6</td>
</tr>
<tr>
<td>11/8/1969</td>
<td>58.1</td>
<td>220.8</td>
</tr>
<tr>
<td>12/6/1966</td>
<td>108.2</td>
<td>382.8</td>
</tr>
<tr>
<td>29/5/1889</td>
<td>85.1</td>
<td>320.7</td>
</tr>
<tr>
<td>30/5/1889</td>
<td>86.4</td>
<td>520.6</td>
</tr>
</tbody>
</table>

d. Triggering mechanisms of convective rainfall

In South China, rain is not a regular feature of monsoonal flow, but a series of periodic events. These events have different triggering mechanisms and scales of organization, but the climatic record and severe storm events have provided some insight into these events. A pulse of vertical motion is required to initiate the development of the storms. During monsoonal flow in May and June, surface front often stretches from 25°N and 107°E to 30°N and 125°E and provides an enhanced environment for storms. Huge thunderstorms are triggered along the front, and they are sustained by upper-tropospheric divergence and lower tropospheric convergence. To the south of this front is a low-level jet where the stratification is unstable, thus the jet provides vertical wind shear required for intense storms. From 1971-1978, Tao and Chen (1987) reported that thirty-eight cases out of the forty cases of heavy storms occurred when low level jet streams were present in the southwest monsoon. However, this synoptic situation does not account for the spatial distribution of observed climatological rainfall patterns in South China, especially along the coastal area.

The results of re-analysis of the rainfall maximum over Hong Kong indicate that heavy rainfall is more correctly associated with a slow moving trough or a quasi-stationary upper level trough (Lam, 1993). In this environment, the boundary layer is warm, moist and conditionally unstable, but the vertical wind shear is not large (Chen, 1969). This produces heavy rain without strong wind and other weather features of severe storms.

The triggering mechanisms for convection over a flat land surface often differ from those over a mountainous area. Over a flat land surface, the triggering mechanism for deep convection often comes from convergence of an atmospheric front, squall lines outflow, or sea-breeze front (Sumner, 1988). Over a mountainous region, the triggering mechanism is generally tied to topographic effects even though vertical wind shears, upper level shortwaves, jet-stream maxima or other synoptic influences can influence the severity of the storms (Banta and Cotton, 1981). The triggering mechanism for convection can either be thermally driven, dynamically driven or both such as mountain-valley circulations, land-sea breeze circulations, orographic lifting, and obstacle effect. Therefore, one needs to fully know the
local circulation when predicting the convection is likely to occur.

Recently, Wai (1993) found a secondary circulation over Hong Kong when he examined the diurnal wind shift in the hourly surface perturbation winds at the Royal Observatory and Waglan Island. The secondary circulation acts like a sea-land breeze and/or upslope-downslope wind. Without calculating the components of the local wind, Wai could not make a clear distinction between the sea-land breeze and upslope-downslope wind because both solar heating and terrain effect produce a similar diurnal wind shift.

Similar to the situation along the western coast of the Indian subcontinent, the dominant monsoonal wind often masks the local winds and local circulations (Ananthakrishnan, 1977). Therefore, knowledge on what role local winds act in the storm developments during summer monsoon in South China is limited. Also little known is how the surface winds interact with the terrain in the storm environment. Their importance in forecasting is undeniable.

e. Objectives of study

To understand the relationship between the local effects and the storm development, we need both observations and theory. The upper air sounding and surface network of winds and air temperature do not always capture the initial storm development. Furthermore, the explicit numerical simulation of the meso-beta scale storms is not feasible because the observational network cannot provide the meso-beta scale model the initial fields. A complete and continuous data record is not available for numerical and diagnostic studies of the storm developments. Therefore as a first step, it becomes necessary to use the conceptual model to help us understand the behavior of the local circulation. If the fundamental questions alluded to the behavior of the local circulations and the interaction between the flow and obstacle are not well understood, the complexity of the storm thermodynamics and dynamics over a complex terrain makes interpreting the model results difficult. Furthermore, results from the conceptual model would help us to better understand the results of numerical simulation and to improve the formulation of the simulation model.

There are four basic aims of this study. The first is to use the conceptual model to quantify any circulations and associated surface forcing mechanisms consistent with those as described by Wai (1993). The second is to illustrate how the local effect can trigger heavy rainfall in a case study. In this study, we only focus on the initiating mechanism. The third is to lay the foundation for a realistic modeling experiment in which we can examine the details of the relationship between the local effect and the storm developments. The results of the simulating study helps with choosing the correct numerical model parameters to further developing storm warning algorithms. Public severe storm warning of several hours is the ultimate goal of this effort. The fourth is to stress that local effects determine the timing and location of heavy rainfall while the synoptic situations determine the severity of the storms.

In sections 3-6, we present a brief development of the conceptual models. A complete analysis can be obtained from either the first or the third author. The discussion of a case study is given in section 7, and the conclusions are presented in section 8.

3. Basic Equations

In this study, we assume that the major axis of the mountain ridge is oriented in east-west direction. We choose a system in which γ (north-south) is parallel and z is perpendicular to the terrain slope (see Pielke, 1984). Using Boussinesq approximation for deep convection, we can obtain the following vector equation of motion:

\[
\begin{align*}
\frac{\partial \mathbf{V}}{\partial t} & = - \mathbf{V} \cdot \nabla \mathbf{V} - \nabla \mathbf{P}^\prime - \mathbf{F} \cdot \mathbf{V} - \nabla \mathbf{P} \mathbf{S} - \mathbf{C}_p \mathbf{P}^\prime \sin \gamma - \mathbf{C}_v \mathbf{P}^\prime \cos \gamma - 2 \Omega \times \mathbf{V} - \mathbf{F} \cdot \mathbf{V} + \rho_0 \nabla \mathbf{V}'
\end{align*}
\]  

(1)

In Equation 1, the subscript (0) represents a larger synoptic scale value and the primed variables are the deviation from a larger synoptic scale value. γ is the slope angle. The second term is the inertial term, the third term is the gradients of perturbation pressure, the fourth term is the horizontal gradient of larger synoptic scale pressure, the fifth and sixth terms are buoyancy, the seventh term is Coriolis term, and the eighth term is friction. Note that \( C_v \mathbf{P}^\prime \) is zero for shallow convection.

Vorticity and circulation

To describe the boundary layer circulation, we first derive the vorticity equation from Equation 1. For simplicity, we assume that the horizontal
gradients of synoptic scale pressure are zero. By using the definition of vorticity \( \zeta = \nabla \times \rho_0 \mathbf{V} \), and \( \nabla \cdot \rho_0 \mathbf{V} = 0 \), we write the time rate of change of vorticity as

\[
\frac{\partial \zeta}{\partial t} = \nabla \times (\nabla \times \rho_0 \mathbf{V}) - \frac{g \rho_0 \nabla (\mathbf{P} \cdot \nabla \gamma)}{\rho_0 C_p P_0} \angle \nabla \times (\nabla \times \rho_0 \mathbf{V}) - \nabla \times (\nabla \times \rho_0 \mathbf{V}) = 0
\]

\[
+ g \rho_0 \nabla \times (\mathbf{P} \cdot \nabla \gamma) \angle \nabla \times (\nabla \times \rho_0 \mathbf{V}) \angle \nabla \times (\nabla \times \rho_0 \mathbf{V}) - \nabla \times (\nabla \times \rho_0 \mathbf{V}) = 0
\]

(2)

In Equation 2, the first term is the local tendency of vorticity; the second term is the gradient of resolvable flux of vorticity and the tilting term; both the third and fourth terms are the solenoidal terms in which vorticity can be created or removed as a result of differential heating; the fifth term is the solid body rotation term as a result of motion on the rotating earth; the sixth term is subgrid scale term (turbulence flux) by small scale motion.

The time rate of change of circulation (C) is then related to the tendency of vorticity (\( \zeta \)) by

\[
\frac{\partial \mathbf{C}}{\partial t} = \rho_0 \nabla \times \mathbf{V} - \frac{g \rho_0 \nabla (\mathbf{P} \cdot \nabla \gamma)}{\rho_0 C_p P_0} \angle \nabla \times (\nabla \times \rho_0 \mathbf{V}) - \nabla \times (\nabla \times \rho_0 \mathbf{V}) = 0
\]

(3)

As given by Equation 2, a spatial gradient in the surface temperature will thermally generate atmospheric circulation. The slope of the terrain will strengthen the differential heating over a heterogeneous surface. The strength of the resultant circulation is directly proportional to the magnitude of the temperature gradient and the depth of the boundary layer to which the temperature perturbation extends (Pearson, 1973). To understand this, we first obtain the equation of vertical motion from Equation 1 by assuming the hydrostatic flow, i.e.

\[
\frac{\partial p}{\partial z} = -g \rho_0 \frac{\nabla \theta}{\rho_0 C_p P_0} \angle \nabla \times (\nabla \times \rho_0 \mathbf{V}) - \nabla \times (\nabla \times \rho_0 \mathbf{V}) = 0
\]

Having taken \( \nabla H \) of Equation 4, we integrate the resultant equation from the surface \( z_s \) to a level \( z \), we obtain

\[
(\nabla H \rho)_b = (\nabla H \rho)_s + \frac{G \rho_0 \Delta z}{\theta_0} \angle \nabla \times \rho_0 \mathbf{V} \angle \nabla \times (\nabla \times \rho_0 \mathbf{V}) = 0
\]

(5)

where \( G = g \cos \gamma \), and \( \theta_0 \) is the mean perturbation temperature over a boundary layer depth (\( \Delta z \)). Therefore the changes of the horizontal wind are proportional to the horizontal temperature gradient and the depth of the boundary layer in which this temperature gradient extends. The changes in the horizontal wind speed will induce surface convergence or divergence and associated vertical wind.

Although differential surface heating can generate circulation, we cannot infer what types of surface wind associated with the circulation from Equation 2. To obtain further insight into local wind regimes and associated physical mechanisms, we can systematically analyze Equation 1 and the temperature equation. The complete set of equations of motion, temperature and continuity is

\[
\frac{\partial u}{\partial t} = -\frac{\partial p}{\partial x} - g \sin \gamma \angle \nabla \times (\nabla \times \rho_0 \mathbf{V}) - \nabla \times (\nabla \times \rho_0 \mathbf{V}) = 0
\]

(6)

\[
\frac{\partial v}{\partial t} = -\frac{\partial p}{\partial y} - g \cos \gamma \angle \nabla \times (\nabla \times \rho_0 \mathbf{V}) - \nabla \times (\nabla \times \rho_0 \mathbf{V}) = 0
\]

(7)

\[
\frac{\partial w}{\partial t} = -\frac{\partial p}{\partial z} - g \tan \gamma \angle \nabla \times (\nabla \times \rho_0 \mathbf{V}) - \nabla \times (\nabla \times \rho_0 \mathbf{V}) = 0
\]

(8)

\[
\frac{\partial \theta}{\partial t} = -\frac{\partial p}{\partial x} \angle \nabla \times (\nabla \times \rho_0 \mathbf{V}) - \nabla \times (\nabla \times \rho_0 \mathbf{V}) = 0
\]

(9)

Having taken \( \nabla \) of Equation 4, we integrate the resultant equation from the surface \( z_s \) to a level \( z \), we obtain

\[
(\nabla H \rho)_b = (\nabla H \rho)_s + \frac{G \rho_0 \Delta z}{\theta_0} \angle \nabla \times \rho_0 \mathbf{V} \angle \nabla \times (\nabla \times \rho_0 \mathbf{V}) = 0
\]

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\[
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\]

(6)

\[
\frac{\partial v}{\partial t} = -\frac{\partial p}{\partial y} - g \cos \gamma \angle \nabla \times (\nabla \times \rho_0 \mathbf{V}) - \nabla \times (\nabla \times \rho_0 \mathbf{V}) = 0
\]

(7)

\[
\frac{\partial w}{\partial t} = -\frac{\partial p}{\partial z} - g \tan \gamma \angle \nabla \times (\nabla \times \rho_0 \mathbf{V}) - \nabla \times (\nabla \times \rho_0 \mathbf{V}) = 0
\]

(8)

\[
\frac{\partial \theta}{\partial t} = -\frac{\partial p}{\partial x} \angle \nabla \times (\nabla \times \rho_0 \mathbf{V}) - \nabla \times (\nabla \times \rho_0 \mathbf{V}) = 0
\]

(9)

\[
\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0
\]

(10)

The upper case \( V \) and \( \theta_0 \) are the basic state variables, and \( u, V, w \) and \( \theta \) are the mesoscale variables. \( \beta = g \theta_0 / C_v p_0 / C_p P_0 \) is the Raleigh friction coefficient. \( \kappa_0 \) is the thermal diffusivity. Rad is the net radiative flux divergence.

4. Downslope Wind

By combining Equations 7 and 9, we can form a second order partial differential equation in \( v \) as

\[
\frac{\partial^2 v}{\partial t^2} + \frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} = \beta \sin \gamma \angle \nabla \times (\nabla \times \rho_0 \mathbf{V}) - \nabla \times (\nabla \times \rho_0 \mathbf{V}) = 0
\]

(11)

\( \Gamma \), the stratification factor, is given by \( \theta_0 / \partial z \). Because of constant slope, the partial differential equations can be written as ordinary differential equations. To obtain equation 11, we assume \( V = 0, w = 0 \), and \( u \) is negligible over a constant slope (\( \partial p / \partial y = 0 \)).
Furthermore, observations indicate that the downslope wind is relatively shallow having a depth on the order of 100 m; therefore, $\Theta \ll \theta$ in the buoyancy terms.

Equation 11 is analogous to the equation of a damped, linear oscillator with constant force. Similar formulations of Equation 11 were solved by Fleagle (1950), and McNider (1982). With initial conditions $v(0) = 0$, and $dv(0) / dt = 0$, we write the complete solution of $v$ as

$$v(t) = \frac{R}{\Gamma \sin \gamma} \left[ \frac{\left( \frac{\sigma^2}{2\alpha_0} \right)^{1/2}}{2\alpha_0} \exp \left( \frac{-\alpha t}{\cos(\omega_0 t - \phi)} \right) \right]$$

where $\alpha_0 = \left( \frac{\sigma^2}{2\alpha} \right)^{1/2}$, and

$$\phi = \tan^{-1} \left( \frac{\sigma}{2\omega_0} \right).$$

The downslope wind is a function of the local cooling rate and inversely proportional to stratification factor and slope angle. The oscillation of the downslope wind depends on the friction coefficient, stratification and slope angle. Figure 5 illustrates two time series of downslope winds (Equation 12) with various values of friction and the stratification factor.

The spatial variation of the downslope wind can be estimated by letting the advection term approximately equal to the buoyancy term. Equation 7 becomes

$$\Delta v = \beta \theta \sin \gamma \frac{\partial v}{\partial y}$$

Therefore, the change in the downslope wind at a distance $\Delta y$ is roughly proportional to the temperature deficit (cooling) and the slope angle. If we take $V = 10$ m s$^{-1}$, $\beta = 9.8/100$ m K$^{-1}$, $\theta = 2$ K, $\Delta y = 500$ m, then $\Delta v$ will vary from 0.5 m s$^{-1}$ at $\gamma = 10^\circ$ to about 3 m s$^{-1}$ at $\gamma = 60^\circ$. Therefore over Hong Kong, the magnitude of the downslope wind ranges from 0.5 m s$^{-1}$ to 1-2 m s$^{-1}$. If the downslope wind blows offshore, it will converge with the onshore monsoonal flow and form a low level convergence leading to the vertical motion near the coastal area.

5. Upslope Wind

During the day, a situation can occur when the buoyancy force is balanced by friction and temperature advection is approximately balanced by the heat diffusion. Then Equations 7 and 9 become

$$\beta \theta \sin \gamma \frac{\partial^2 v}{\partial y^2} = 0$$

$$-v \Gamma \sin \gamma \frac{\partial^2 v}{\partial y^2} = 0$$

In Equation 14, we replace the Raleigh friction with the eddy diffusivity. Combining Equations 14 and 15, we can obtain a governing equation of temperature for the upslope wind, i.e.

$$\frac{\partial \theta}{\partial z} + \beta \Gamma \sin \gamma \frac{\partial^2 \theta}{\partial y^2} = 0$$

Prandtl (1952) provided the solution of a similar form of Equation 16. Using the surface and upper boundary conditions, we obtain the vertical temperature profile as

$$\theta(z) = \theta_s e^{z/m} \cos(\pi z/m)$$

where $\theta_s$ is the surface temperature perturbation and $m = \left( \frac{4 \kappa \kappa_s}{\beta \Gamma \sin^2 \gamma} \right)^{1/4}$

Once (z) is known, we can calculate the vertical profile of upslope wind by differentiating Equation 15 twice; i.e.

$$v(z) = \theta_s \Gamma \kappa \kappa_s \theta_s^2 \sin(\pi z/m)$$

The strength of upslope wind does not depend on the slope angle; it only depends on the surface temperature perturbation, square root of thermal eddy diffusivity and inversely depends on the square root of friction coefficient and stratification. Therefore, the upslope wind is intensified with strong local surface heating and turbulence heat transfer along with small surface friction under unstable condition. One such vertical profile of the upslope wind (Equation 18) is shown in Figure 6. From the wind profile, we can infer that the upslope wind and the return flow aloft form a close circulation. During the summer months over Hong Kong the upslope and is masked by the dominant monsoonal flow.
6. Different Wind Systems

a. Over a differential heating surface

In the previous sections, we examine the wind system in terms of local heating and cooling. In this section, we focus on the wind system over a heating length scale on the order of 10 to 100 km. The wind system, such as the sea-land breeze, has been studied by Stem and Malkus (1953), Olfe and Lee (1957), Kimura (1975), Martin and Pielke (1983), Rotunno (1983), Hsu (1987), and Niino (1987). Most of these studies have been focused on two questions. The first is being what determines the horizontal scale of the sea-breeze, and the second is the adequacy of the hydrostatic assumption in the sea-land breeze numerical model. In this study, we are interested in the behavior of the boundary layer circulation over a heating surface. To solve for the vertical motion field, we apply a mathematical approach similar to Ma and Wai (1991). For simplicity, we consider the flows over a flat surface.

Equations 6-10 become

$$\begin{align*}
\frac{\partial u}{\partial t} & = -v \frac{\partial u}{\partial y} + f v - c u \quad (19) \\
\frac{\partial v}{\partial t} & = -v \frac{\partial v}{\partial y} - \frac{\partial p}{\partial y} - c v \quad (20) \\
\frac{\partial w}{\partial t} & = -v \frac{\partial w}{\partial y} + \frac{\partial p}{\partial z} + \beta \theta - c w \quad (21) \\
\frac{\partial \theta}{\partial t} & = -v \frac{\partial \theta}{\partial y} - \omega \frac{\partial \theta}{\partial z} + \frac{g^2 \theta}{\partial z^2} \quad (22) \\
\frac{\partial v}{\partial y} & = 0 \quad (23)
\end{align*}$$

To obtain the vertical motion field from the equations, we first convert Equations 19-23 to ordinary differential equations via the Fourier transform, which has each dependent variable expressed as

$$\Psi(y, z, t) = \sum_k \phi_k e^{i k y} e^{i \omega t}.$$ 

Applying the Fourier transform to the governing equations, we can obtain a coupled ordinary differential equation in $\theta$, which are further combined into one equation in $\theta$ as

$$\frac{d^4 \theta}{dz^4} - (a_1 + b_1) \frac{d^2 \theta}{dz^2} + (a_2 b_1 + a_2 b_2) \theta = 0 \quad (24)$$

---

Figure 5 Time series of the downslope wind speed for two situations. (1) Temperature lapse rate in 2.7 K km$^{-1}$ and local cooling rate equal to 1 K h$^{-1}$ (solid line). (2) Temperature lapse rate in 8 K km$^{-1}$ and local cooling rate equal to 0.5 K h$^{-1}$ (dashed line). The slope angle remains 30 degrees.

Figure 6 Vertical profile of upslope wind in m s$^{-1}$ with the temperature perturbation equal to 10 K.
where \( a_1 = \frac{\kappa}{\pi} \left[ \bar{\omega} + \bar{V} \right] \phi \left[ \bar{\omega} + \bar{V} \right] + \sigma^2 + \frac{\tau^2}{2} \right], \\
a_2 = \frac{\kappa}{2} \left[ \bar{\omega} + \bar{V} \right] \phi \left[ \bar{\omega} + \bar{V} \right] + \sigma^2 + \frac{\tau^2}{2}, \\
\text{and} \\
b_1 = \frac{\bar{\omega} + \bar{V}}{\kappa} , b_2 = \frac{\tau}{\kappa}.

A similar form of Equation 24 was solved by Martin and Pielke (1983), and Hsu (1987). Using the boundary conditions,

\( \bar{\theta} = 0 \) at \( z = -\infty \), \( \bar{\theta} = \frac{\bar{\tau}}{2} \) at \( z = 0 \)

and

\( d^2 \bar{\theta}/dz^2 = b_1 \bar{\theta} \) at \( z = 0 \) and \( z = -\infty \),

we obtain the solution of Equation 24 as

\( \bar{\theta} = \frac{\bar{\tau}}{2} \left[ b_2 - b_1 \right] e^{-\lambda_1 z} + \left[ b_1 - b_2 \right] e^{a_2 z} \)

(25)

where

\( \lambda_1 = \frac{1}{2} \left[ a_1 + b_1 \right] + \frac{1}{2} \left[ a_2 - b_2 \right]^{1/2}, \)

(26)

\( \lambda_2 = \frac{1}{2} \left[ a_1 + b_1 \right] - \frac{1}{2} \left[ a_2 - b_2 \right]^{1/2}, \)

(27)

In Equation 25, \( \bar{\tau} \) is the surface heating function of space and time. When \( \bar{\theta} \) is obtained, one can calculate \( \bar{W} \) from the coupled equation as

\( \bar{W} = \frac{\bar{\tau}}{b_2 \lambda_2 - \lambda_1} \left[ b_2 - b_1 \right] \left[ e^{a_2 z} - e^{a_1 z} \right] \)

(28)

The solutions of \( \theta \) and \( w \) in the physical space are obtained by the inverse Fourier transform.

In Equation 28, the vertical motion in the circulation is directly proportional to the differential surface heating. Additional insight into the circulation can be gained by examining all the parameters associated with the vertical motion. From Equations 19-23 we can derive a fourth order partial equation in \( \bar{W} \) as

\( \frac{d^4 \bar{W}}{dz^4} - \left( a_1 + b_1 \right) \frac{d^3 \bar{W}}{dz^3} - \left( a_2 - b_2 \right) \frac{d^2 \bar{W}}{dz^2} - \left( a_1 b_1 - a_2 b_2 \right) \bar{W} = 0 \)

(29)

To examine the relative importance of these parameters in the circulation, we can nondimensionalize Equation 29 with the following scales: the local heating length scale \( L \) for \( \bar{\omega} \) or \( 1/\kappa \), the scale height \( D \) for \( z \), the horizontal mean wind scale \( \bar{V} \) for \( \bar{V} \), the time scale \( V/L \) for frequency \( \omega \), and \( V/L \) for \( \sigma \). A scaled equation for \( \bar{W} \) is written as

\( \frac{d^4 \bar{W}}{dz^4} - \left( a_1 + b_1 \right) \frac{d^3 \bar{W}}{dz^3} - \left( a_2 - b_2 \right) \frac{d^2 \bar{W}}{dz^2} - \left( a_1 b_1 - a_2 b_2 \right) \bar{W} = 0 \)

(30)

where

\( a = -k^2 \left[ \bar{\omega} + \bar{V} \right] \phi \left[ \bar{\omega} + \bar{V} \right] + \omega^2 + R_0^2 \)

(31)

\( b = \frac{\bar{\tau}}{2} \)

(32)

\( c = \frac{\bar{\tau}}{2} \left[ \bar{\omega} + \bar{V} \right] \phi \left[ \bar{\omega} + \bar{V} \right] + \omega^2 + R_0^2 \)

(33)

The three parameters are

\( R_0 = \frac{\bar{V}}{\bar{V}}, \)

\( D_0 = \frac{\bar{V}}{\bar{V}} L^{1/2}, \)

\( D_0 = \frac{\bar{V}}{\bar{V}} N^{1/2}, \)

where \( N \) is the buoyancy frequency.

In addition to the aspect ratio \( D/L \) of the local heating length and the scale depth of boundary layer, three additional important parameters are Rossby number \( R_0 \), diffusive depth scale \( D_0 \), and stratification depth scale \( D_0 \). The Rossby number determines the relative importance of the rotational effect in the circulation. In the expression for the coefficient \( a \), there is a critical wave number which can bring the value of coefficient \( a \) to infinity if \( \sigma \) is zero. This critical number corresponds to the inertial wave. When \( R_0 \) approaches unity, the inertial oscillation will dominate the local circulation generated by the surface heating. When \( R_0 \) is increased by one order of magnitude to 10 while all other parameters remain unchanged, an out-of-phase of forced circulation with a descending motion is found over the heating surface and an ascending motion downwind appears. The inertial oscillation can be removed by keeping \( R_0 \) away from approaching unity. A second parameter, the diffusive depth scale (Equation 32), is proportional to the square root of the thermal eddy diffusivity and the heating length scales and inversely dependent on the mean wind.
speed. Therefore strong thermal eddy diffusion and large heating length will give a strong vertical motion and circulation depth. However, strong mean wind speed can suppress the vertical motion. A third parameter, the stratification depth scale (Equation 33), is proportional to the wind speed and inversely dependent on the vertical thermal stratification. Therefore, the mean wind speed can also increase the vertical motion while the thermal stratification limits the vertical motion. Hsu (1987) and Ma and Wai (1991) illustrated various types of circulations graphically over a heating surface.

b. Under a stratified condition

We have considered three wind systems and associated vertical motion under various surface heating and cooling. Forced vertical motion can also occur when the stratified surface flow interacts with an obstacle. In this situation, neither surface heating nor surface cooling is needed. Since Hong Kong consists of the some 200 islands and three main mountain chains, it becomes important to understand the effects of the islands and mountain chains on the surface flow. In this section, we only consider the steady flow of a vertically unbounded, inviscid fluid over a small amplitude topography given by

\[ z = h(x, y) = h_m \left( \frac{r^2}{a^2} + 1 \right)^{3/2}, \]

where \( h_m \) is the maximum height of the obstacle, \( r = \left( x^2 + y^2 \right)^{1/2} \), \( a \) is the radius of the obstacle. We use the ideal topography in order to obtain the solution to the equations. Equations 6-10 are reduced to

\[
\begin{align*}
\n\frac{\partial u}{\partial y} + \frac{1}{\rho_0} \frac{\partial p}{\partial x} &= 0, \\
\frac{\partial v}{\partial y} + \frac{1}{\rho_0} \frac{\partial p}{\partial y} &= 0, \\
\frac{\partial w}{\partial z} + \frac{1}{\rho_0} \frac{\partial p}{\partial z} &= 0, \\
\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} &= 0.
\end{align*}
\]

where \( B \) is the buoyancy term. In Equation 34, we include the zonal pressure gradient term because the perturbation flow in this case is a three dimensional flow. By eliminating the pressure gradient terms in Equation 34-36, and making use of the kinematic condition for a steady flow, we write

\[
\frac{\partial^2}{\partial y^2} \left( \nu^2 \delta \right) + \frac{\nu^2}{\nu H} \frac{\partial^2}{\partial z^2} \delta = 0
\]

(38)

where \( \delta \) is the vertical displacement of a fluid parcel. Applying a double Fourier transform to Equation 38, we obtain an equation of \( \delta \) with respect to \( z \):

\[
\frac{\partial^2}{\partial z^2} \delta + M^2 \delta = 0
\]

(39)

where

\[
M^2 = k^2 + \frac{1}{2} \left( \frac{N^2}{k^2} - \frac{1}{2} \right)
\]

The formulation of Equation 39 is similar to those solved by Wurtele (1957) and Smith (1980). Assuming that \( N^2 \) is constant, we obtain the solution of Equation 39 as

\[
\delta(k,l,z) = \delta(k,l,0) e^{i(mk,0)z}
\]

(40)

Using the linear lower boundary condition of the mountain shape which is given by

\[
\xi(k,l,0) = \xi(k,l),
\]

we obtain the solution of the vertical displacement of the fluid parcels as

\[
\delta(k,l,z) = \int \xi(k,l) e^{i(mk,0)z} dk \, dl
\]

(41)

When \( \delta \) is known, we can calculate the pressure field via the hydrostatic relationship. Then one can calculate the horizontal wind velocities using Equation 34 and Bernoulli's equation:

\[
u(x,y,0) = -Nh \frac{ax}{1 + \frac{r^2}{a^2}}
\]

(42)
There are two interesting features when the stratified flow approaches an obstacle. The first is a situation when stagnation ($V = 0$) occurs on the windward slope of the obstacle. Subsequently, the reversal flow occurs over the windward obstacle and forms a separating line with the mean flow. Convections develop along this separating line. The numerical study (Smolarkiewicz, 1988) indicates that the formation of the reversal flow does not require neither the downslope density current nor thermally driven land breeze; it is a result of the interaction between the mean flow and the obstacle. As given by Equation 43, the stagnation roughly occurs at $(x, y, z) = (0, -0.7a, 0)$ when $v$ becomes equal but opposite to $V$ and the Froude number ($Fr = hN/V$) $= 3$. Here $V$ is the mean boundary layer wind upstream. When the Froude number is decreased to 0.1, the effect of nocturnal cooling becomes increasingly important and downslope wind will dominate (Chen and Nash, 1994).

The occurrence of the stagnation points depends on hill shape and ambient shear (Smith, 1989). When the obstacle is relatively narrow, the stagnation occurs at the surface. Then the stratified surface air is forced to pass around the obstacle, only air parcels originate at higher elevations are able to lift over the obstacle. Therefore, it is difficult for stratified air to rise over the obstacle. Because of flow splitting the second interesting feature is the lateral deflection ($\delta$) of the flow adjacent to the obstacle. We can calculate $\delta$ by integrating the following equation

$$\delta(x,y,0) = \frac{1}{V} \int u(x,y,0) \, dy$$

(44)

The integration of Equation 44 is

$$\delta(x,y,0) = \frac{-Nh}{V} \frac{x}{1 + x^2/a^2} \left( \frac{y/a}{(1 + x^2/a^2)^{1/2}} \right)$$

(45)

The $\delta$ field, as given by Equation 45, is shown in Figure 7. On the eastern side of the obstacle, the southerly air parcel experiences higher pressure on its left; therefore the air parcel is deflected to its right. Horizontally, the distant air parcel will not experience high pressure; the air parcel will relatively maintain its northward direction. Similarly, the air parcel to the west of the obstacle will be deflected to its left. The condition for part of the surface flow to deflect laterally can be evaluated at $y = 1$ in Equation 45. When $\delta = a/2$, the lateral deflection occurs at $x = a$ when Froude number is equal to 1. As the flow near the obstacle is deflected laterally, the flow converges and leads to vertical motion.

7. Discussion

The objective of constructing the conceptual models is to allow each triggering mechanism to be classified and understood. The verification of these triggering mechanisms in the local heavy rainfall cannot be achieved at the present time due to the lack of a meso-beta scale data set sufficient for comprehensive studies of storm developments. Another complexity to the problem is the Hong Kong complex terrain. Therefore, a discussion of the predictability of such torrential rainfall events based on the

Figure 7 Surface streamlines of hydrostatic flow past an isolated obstacle. Horizontal deflection of the surface flow occurs in the areas adjacent to the obstacle.
triggering mechanism is beyond the scope of the present study. However, we can apply the conceptual models to explain the trigger of the local heavy rainfall.

In this study, we select RS93 because Song (1994), Lam (1994), and Lee et al. (1994) have discussed various aspects of the storm. In short, Song described the synoptic situation of the storm and its complex meso-scale features. The synoptic situation provided a conditionally unstable atmosphere favorable for convections. Using analyses of the 15-minute rainfall rate, Lam (1994) tracked the storm across the territory. The analysis of 30-minute surface air temperature and surface winds inferred from the local automated weather stations revealed the penetration of cool surface easterly winds and the retreat of warm moist southwesternly. Therefore Lam suggested that the heavy rainfall over the territory is induced by the wedging effect. Furthermore, Lee et al. show both the positive correlation between the peaked hourly rainfall and the onset of the eastern component of the surface wind at the Royal Observatory. In addition to what have been discussed, we examined the surface winds and temperatures, radar observations, and rainfall distribution.

a. Surface winds and temperatures

The mesoscale surface high pressure approached Hong Kong from the east around dawn on June 16. By 1000, cooler easterly prevailed in the eastern half of Hong Kong while the warm, moist southwesternly wind gradually retreated westward in the western half of the territory. Two surface winds formed a confluence line. Around 1100, a warm pool of surface air was located in the southwestern sector. The surface temperature difference across the territory was about 5 degrees. The surface wind in the northwestern quadrant was more likely northeasterly because a tongue of cool surface air penetrated to the urban area from the northeast parallel to the Ma On Shan chain (Lee et al., 1994). As the southwesternly retreated westward, easterly wind spread across Hong Kong complex terrain leading to a complicated flow pattern. The upper air sounding at King’s Park indicated that the layer of cooler surface wind amounted to about 500 m. At 1130, the confluence line, approximately in the northeast-southeast direction, was located in southwestern quadrant of the territory. By 1300, the confluence line moved southwards and left the territory.

b. Radar observations

Around dawn, radar images revealed multiple sizes of numerous convective cells over the lower Pearl River basin. Some of these cells dissipated while others grew and intensified, or merged into a super cell. To track the movement of the cells, we chose Lantau Island as a reference point because the island remained visible on the radar almost the entire morning of June 16. The island was not affected by the rain storm until midday.

At 0400, the convection cells formed a convection line, which was found along the coastal zone east of the estuary. Noted that the coast line in South China is roughly in the southwest-northeast direction. For the next 2-3 hours, the convection line was basically quasi-steady even though the cells had gone through various changes. By 0800, the northeastern section of the convection line moved southeastward over to the open water. However, the southwestern section of the convection line drifted southwestward along the coast and the convection cells also intensified. Between 1000-1200, the southwestern section of the convection line was over the territory and produced the torrential rainfall in Hong Kong.

c. Rainfall patterns

The daily accumulated rainfall of RS93 over Hong Kong showed two local maxima. One was an elongated belt parallel to the east of Ma On Shan. The other maxima was found near Tuen Wan (south of Tai Mo Shan and west of Ma On Shan chains). The peaked rainfall between 1000-1300 also showed two similar maxima. Another striking feature of RS93 was that the orographic rain was substantially less than those in previous rain storms. For instance, topographic effect produced the maximum rainfall along the mountain crests in RS82, RS72, and RS66. Therefore it is interesting to explain what mechanism produces the observed local rainfall maximum in RS93.

d. Triggering mechanism for heavy rainfall

Before explanation is given, we summarize the characteristics of RS93. First, the heavy rainfall was not located in a uniform belt parallel and adjacent to the confluence line between the cold and warm air (Lam, 1994). The heavy rainfall was marked by mesoscale cells of local maximum. The orographic rain along the mountain crest was substantially less than the local maximum. The phenomenon of drier peak was not usually found in most storms. Since the depth of surface cool air was about 520 m, the cold surface air was unable to climb over most of the peaks in Hong Kong. For instance, the peaks along the east-west mountain chain over Hong
Kong Island are over 520 m. Similarly, Ma On Shan and Tai Mo Shan chains over Hong Kong Mainland include peaks over 600 m. Therefore, surface cool air was forced to flow around the peaks resulting in complicated surface flow patterns. The situation made the wedging effect over the rugged terrain difficult. However, in some areas, such as High Island Reservoir, some surface cool air could be lifted over the terrain because the terrain heights are below 500 m.

Considering the observed surface wind, temperature, and rainfall maximum which are consistent with the conceptual model, we conclude that the heavy rainfall event is initiated by the interaction between the stratified flow (cooler surface wind) and Ma On Shan chain. The lateral deflection of the surface wind adjacent to the Ma On Shan chain converges with the easterly wind in the southeast quadrant and triggers a deep convective cell there. The location of the convergence, which is predicted by Equation 45, corroborates with the location of the maximum rainfall adjacent to the Ma On Shan chain. Although wedging effect can induce rising motion and is important over the open water, it can not explain the observed local maxima in the territory. Therefore, the wedging effect of the cold air was not a primary mechanism to initiate the heavy rainfall event as it was suggested by Lam (1994). Finally, Watanabe and Ogura (1987) reported a similar heavy rainfall event resulting from the flow deflection by a mountain range over Japan. The second maximum near Tsuen Wan was more difficult to explain because of surface flow pattern and the interaction between the complex terrain and the storm dynamics.

The atmospheric stability can also control the ability of the warm, moist air to climb over a mountain and the enhancement of rainfall. We illustrate the effect by comparing the rainfall distribution in a group of Hawaii Islands with varying heights but all exposed to the same trade wind. Several islands with peaks such as Koolau Range (700 m), Kauai (1400 m), Molokai (1400 m) and West Maui (1700 m) show maximum rainfall at their peaks because the trade wind can rise over the peaks and produce orographic rain (University of Hawaii, 1983). However, peaks East Maui (3000 m) and Mauna Kea (4300 m) are too high for the trade wind to climb. Therefore the maximum rainfall is found on the windward coast and the peaks are drier.

The analyses of other storms were largely aimed at the synoptic scale storm environments. Therefore, we found the analyses difficult to identify the local triggering mechanism. However, the hourly rainfall patterns in RS66 suggested that the initial rainfall maximum could be related to the local effect. In the case of RS66, relatively heavy rainfall began over the harbour south of Tao Mo Shan at 0400 on June 12 (Chen, 1969). This area of heavy rainfall occurred within a coastal band of higher frequency of strong radar echo (higher frequency indicated) as indicated by the summer radar echo climatology (Cheng and Kwong, 1973). This region of a higher frequency of rainfall could be explained by the interaction between the local downslope wind/land breeze and the monsoonal flow (Wai et al., 1995). Furthermore, orography effect was another local rain-producing mechanism along the mountain crests, as shown in RS66 and other storms.

8. Conclusions

The climatic rainfall patterns on regional and local scales in South China indicate that the summer non-tropical cyclone rainfall is associated with localized convective storms. The maximum rainfall of these storms are concentrated in the Pearl River delta. The frequency of these storms shows a high percentage of occurrence near day break or at midday. Therefore, the development of these storms requires local circulations as initiating mechanisms.

The linear analyses of dynamic and thermodynamic equations indicate that local circulations are associated with the downslope wind, the upslope wind and the sea-land breeze. These surface winds constitute the secondary circulation over Hong Kong (Wai, 1993) as they are masked by the monsoonal wind. The primary forcing mechanisms are surface cooling and terrain for the downslope wind, surface heating for the upslope wind and differential surface heating for the sea-land breeze. When the downslope wind or the land breeze converges with the monsoonal flow, the low level convergence of flows will initiate convection. Similarly, the upslope wind and the sea breeze readily lift warm, moist air to saturation and produce heavy rainfall. The blocking effect (Elliott and Hovind, 1964) and deflection of the low-level stratified wind can also trigger deep convection upstream or in the areas adjacent to the mountain range. The surface moisture flux, which is not considered in the analysis, is another important source of heating in the storm developments. Therefore, a full explicit numerical simulation is required to investigate how the complex terrain interacts with the storm.

To predict the summer storms successfully over Hong Kong complex terrain, the forecasters are required to understand the relationship between...
the synoptic scale and mesoscale forcing. The synoptic scale sets the stage for and determines the likelihood of deep moist convection. In South China, the synoptic scale processes generally provide moist environment and stability. The mesoscale or smaller scale determines the timing and location of the storm. Over Hong Kong when synoptic winds interact with local circulations or with the terrain, the results of interaction can provide localized pulses of vertical motion that can trigger moist convective cells. Since 1966, a great amount of effort has been dedicated to re-analyze synoptic-scale kinematic fields of severe storms; the results of these re-analyses have led to recognition of basic storm environments and types. The knowledge of local effects in local storm developments remains at its infant stage; therefore a considerable amount of effort is required to seek better understand the relationship between local forcing mechanisms and storms by means of diagnostic and numerical simulation studies. After all, local effects determine the timing and location of heavy rainfall while the synoptic situations determine the severity of the storms.

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Appendix I:

Physical Relief of South China

In analysis of the variability in Hong Kong's regional rainfall pattern, we need to consider not only the differences in the atmospheric circulation, but also the influence of the landforms in South China.

The Nanling system near 25°N, 113°E is one of the three Giant Latitudinal Structure Systems, a great geographic divide between south China and central China. The Nanling system is composed of three sections which stretch from west to east more than 600 km and from north to south for about 200 km. The western section has a southwest-northeast axis with peaks about 2000 m in elevation along Guangxi, Hunan and Guangdong provinces. The middle section is mainly a west-east trending with peaks of about 1000 m along the border of Guangdong and Hunan provinces. The eastern section is generally below 1000 m.

The Lingnan (south of Nanling) region is dominated by low mountains and hills below 1000 m in elevation (Figure 1). There are a few mountains with peaks about 1000 m. The landscape of southwestern Guangdong is mainly composed of plain and terrace below 100 m in elevation interspersed with low hills. Western Guangdong is dominated by two southwest-northeast mountain chains. In eastern Guangdong the terrain is mostly marked by seven chains of low mountains and hills which are parallel to the coast.

Hong Kong shares the attributes of Guangdong province in both geological and geomorphological structures. The landscape of Hong Kong is dominated by low mountains and hills. Hong Kong mainland is marked by three ridges running southwest to northeast. The first ridge begins with Ma On Shan (702 m) and branches out to Kowloon Peak (602 m) to the south west and Lion Rock (495 m) to the west. The second chain includes Tai Mo Shan (957 m), the highest peak, extends southwestward to Sunset Peak (869 m) and Lantau Peak (933 m) on Lantau Island. The northern and northwestern areas are covered by plains and valleys with smaller ridges below 650 m. On the island of Hong Kong itself, a main east-west line of ridges begins with Mount Parker (531 m) and ends with Victoria Peak (552 m). Low ridges in southern Hong Kong are oriented north-south.

The most important river system in Guangdong is the Zhu Jiang (Pearl River) which is composed of three main tributaries: Xi Jiang (West River), Bei Jiang (North River), and Dong Jiang (East River). The Pearl River empties into the South China Sea between Macau on the west and Hong Kong on the east.

The Pearl River delta is basically an alluvial basin, and the coastal areas are hilly. Elsewhere from west to east, Yunwu Shan, Nanling, Juilian Shan and Lianhua Shan are arranged an arc. Because of the varying landforms in the areas of Lingnan, the variability of annual rainfall is large with some windward slopes recording more than 2000 mm, and isolated valleys less than 900 mm. The distribution of precipitation shows local maxima which are characteristic of mesoscale terrain influences.
Appendix II: Data

a. Rainfall data

We base our analysis of the spatial and temporal variation of rainfall on three data sets. The first is the Climate Data of the People’s Republic of China (PRC) from 1841 to 1988. This data base consists of surface meteorological records from 296 stations, which are organized into five data sets in accordance with a joint research agreement between the PRC Chinese Academy of Sciences (CAS) and the Carbon Dioxide Information Analysis Center (CDIAC) of the United States Department of Energy in 1987. Tao et al. (1991) have highlighted the organization of these five data sets. In this study, we selected stations Shaoguan (SHA), Guangzhou (GUZ), Heyuan (HEY), Shantou (SHT), Haifeng Shantwei (HAS), Yangjiang (YAJ), and Zhanjiang (ZHJ). All these stations are located in Guangdong province. Additional surface meteorological elements between 1988 and 1993 for stations Guangzhou and Shantou are obtained from the Monthly Climatic Data for the World, which are published by the National Climatic Data Center of the United States Department of Commerce in cooperation with the World Meteorological Organization.

The second set of rainfall data is based on Hong Kong surface meteorological records for 72 years from 1884 to 1939 and from 1947 to 1962 (RO, 1963). From 1963 to 1993, the rainfall data are based on the Monthly Climatic Data for the World. Similarly, the rainfall data at Macau (MAC) are also based on the Monthly Climatic Data for the World, and data from Servicos Meteorologicos e Geofisicos, Macau.

Since 1969, the staff at the Royal Observatory (RO) have documented the hydrometeorological aspects of nine rain storms (RS) in the forms of technical reports. The nine storms are RS93 (Song, 1994; Lam, 1994; Lee et al., 1994), RS92 (Lam 1993), RS89 (Lam, 1994), RS83 (Lee, 1983a), RS82 (Lee, 1983b), RS72 (Cheng and Yerg, 1979), RS69 (Lam, 1975), RS66 (Chen, 1969), and RS889 (Chan, 1976). RS889 refers to the rain storm in 1889. In particular, there were lengthy discussions of the hourly patterns of rainfall rate over Hong Kong. In several reports, the staff also described the large-scale kinematic fields of the storms. In this study, we extend their studies of synoptic forcing in these storms. The hourly observations of surface data at the Royal Observatory during the transition of these nine storms are also used to study the timing and intensity of the storms.

b. Quality of the rainfall data

Because the PRC data contain long records of many surface meteorological elements, CDIAC has conducted quality checking of the data. Given a vast data record of surface meteorological elements, some erroneous and inconsistent values in the data files are inevitable. In the case of the precipitation data, CDIAC focused on researching very high totals and nonzero totals repeated over consecutive observing periods. The high rainfall totals at the coastal stations during summer monsoons are considered valid. More details of the quality of the CAS data have been discussed by Kaiser et al. (1993).

In the case of the rainfall data at the Royal Observatory, the technical staff routinely checked for consistency, reliability, and accuracy of the rainfall data. Calibrations are done when necessary (Chen and Kwok, 1966; Cheng, 1971; Chen, 1974). A notable study is that of Peterson (1964), who evaluated the reliability and representative of the rainfall at the Royal Observatory. Based on a sample of rainfall data from 94 rain gauges over the entire Hong Kong between 1952-1962, Peterson found that the annual mean rainfall of all 94 rain gauges (2271 mm) is quite close to the mean annual rainfall at the Royal Observatory (2205 mm). Peterson concluded that the mean annual rainfall at Royal Observatory is reasonably representative of the entire Hong Kong region. For the rainfall rates we have made extra efforts to resolve quality issues involving late reports and corrections of rainfall data, whether published in the Monthly Climatic Data for the World, or obtained directly from the Royal Observatory and the Servicos Meteorologicos e Geofisicos at Macau.
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Froude Number Statistics for Northerly Cold Surges in Southern China

ABSTRACT

The Froude number (Fr) statistics using both ECMWF data and meteorological station data are presented for northerly cold surges invading the coast of southern China and Hong Kong, with a view to developing a reliable predictor for cold surges passing over the Nanling Range; the arrival of such surges are defined by a temperature drop of 3°C or more, or prevailing wind (of 5 m s⁻¹ or more) shifting to the range 330° to 030°, as measured by a station south of the Nanling Range, e.g., Hong Kong. It is found that if the pressure difference between the station Chenzhou and Hong Kong Δp exceeds 7 hPa, then the cold surge will arrive in the coast of southern China 12 to 24 hours later if Fr > 0.9 and will not arrive if Fr < 0.8. In the 0.8 to 0.9 range, the indeterminacy can be resolved by in addition using a geopotential height difference ΔZ on the 850 hPa surface in the vicinity of the Nanling. Such a forecasting index pair gives unambiguous predictions for the arrival of northerly cold surges in southern China.

1. Introduction

1.1 Prediction of cold surges passing over the Nanling range

Outbursts of winter monsoons often bring northerly cold surges which invade the coast of southern China, including Hong Kong. These surges cause significant temperature drops (typically over 3°C) and bring strong north to north-east winds (wind speeds typically over 5 m s⁻¹). It is obviously important to develop reliable predictors for these surges.

The ultimate cause of such cold surges is the synoptic development of upper level systems and surface cold air masses built up by continuous advection from the arctic region. However, the immediate dynamic cause would appear to be the north-south pressure gradient. According to Lai (1989), a useful practical parameter for expressing this gradient is the pressure difference between station 57972 (Chenzhou, 113°E, 26°N) and Hong Kong (114.2°E, 22.3°N), hereafter denoted as Δp. First of all, a potential cold surge event is placed under close scrutiny if Δp > 7 hPa. Then in terms of Δp, Lai (1989) proposed the following forecasting rule: If Δp > 8 hPa and subsequently increases by 2 hPa or more within six hours, then the cold surge would arrive in Hong Kong within 12 to 24 hours.

While Δp is certainly a parameter of critical importance, its use alone can lead to indeterminacy and false alarms. This can be illustrated by the cold surge which arrived in Hong Kong on 5 January 1991. The synoptic charts at mean sea level are depicted in Figure 1, and Figure 2 shows the time series of Δp together with the time series of temperatures recorded in Hong Kong; the third trace, for the Froude number Fr, will be explained later. There are two very similar peaks in the Δp trace, occurring respectively at about 0600 UTC on 1 January and at about 1800 UTC on 4 January. In each case, Δp had first exceeded 8 hPa, and had then shown a further increase of about 2 hPa or more. According to the Δp rule, the predictions in these two cases should have been the same. Yet, in the first instance, a cold surge did not materialize over the next two days, whereas in the second instance, the cold surge, with a very substantial temperature drop, was recorded in Hong Kong only a few hours later.

The indeterminacy is hardly surprising, since the north-south pressure gradient is not the only factor that affects the development of the surge; the orographic effect must be important as well. In particular, the Nanling Range, lying roughly along 26°N and from 110°E to 116°E, with an average height of 600 m (Figure 3), often blocks the cold surges. For the same Δp in the north,
the temperature drop in the southern coastal region in the subsequent period (12 to 24 hours) depends critically on whether the surge succeeds in passing over the Nanling Range. Therefore it will be interesting and important to look for a forecasting index that incorporates orographic blocking.

1.2 Theoretical studies on orographic blocking and the Froude number

Three physical factors are relevant to orographic blocking: the wind speed \( U \) tending to drive the cold air over the barrier, the height of the barrier \( H \), and the vertical stability of the atmosphere due to density stratification. The last of these can be measured by the Brunt-Vaisala frequency, \( N \), which expresses the natural frequency of oscillations when the vertical equilibrium between buoyancy and gravity is disturbed. This is given by (Holton, 1992)

\[
N^2 = g \frac{d \log \theta}{dz}
\]  

(1)

Figure 1 Mean sea level pressure charts for 1 January to 5 January 1991 (From Monthly Weather Summary, published by ROHK recorded at 0200 H.K. time)
Figure 2  Time series of $\Delta p$ (upper, 6-hourly records), temperature recorded at ROHK (middle, 6-hourly records and $Fr$ (lower, 12-hourly records) from 31 Dec. 90 to 5 Jan. 91.

Figure 3  The contour showing orography of southern China
where \( g \) is the acceleration due to gravity, \( \theta \) is the potential temperature and \( z \) is the height. Constant \( \theta \) corresponds to an atmosphere in neutral equilibrium. If \( \rho \) is the ambient density at the lower level, one may regard

\[
k = \rho g H^2
\]

as the effective force constant of a "spring" restraining the vertical movement of a unit volume of air mass.

The Froude number \( Fr \) is a dimensionless parameter formed out of these quantities:

\[
Fr = \frac{U}{NH}
\]

and should be important in characterizing fluid motion in which the balance between gravity and buoyancy is significant (Kundu, 1990). One expects that if \( Fr \) exceeds some critical value \( Fr_c \), then the cold surge would pass over the barrier. According to Sheppard (1956), Baines (1979) and Gill (1982), air flow would be blocked by a barrier if the kinetic energy of the air in the low level is less than the potential energy required to get over the barrier. The kinetic energy per unit volume is \((1/2) \rho U^2\), while the potential energy required for climbing over a barrier of height \( H \) is \((1/2) \rho g H^2\), which is easily derived by reference to (2) for the effective force constant of the "spring" that restrains vertical motion. Hence, the air flow would be blocked if

\[
\frac{1}{2} \rho g U^2 < \frac{1}{2} \rho g N^2 H^2
\]

or

\[
Fr^2 < 1
\]

This heuristic argument identifies \( Fr \) as an important parameter, and suggests that \( Fr \sim 1 \). An alternative derivation has been given by Gill (1982).

Orographic blocking effects play an important role in many weather systems around the world, for instance, in Appalachian cold air damming (Bell and Bosart, 1988). In the literature, the blocking effects have been studied both theoretically and experimentally, often in terms of the Froude number. Long (1953) considered an incompressible frictionless stratified flow around a non-rotating mountain range, and discussed the solution of the linearized governing equations. Later, Miles (1968a, 1968b), Miles and Huppert (1969), Huppert and Miles (1969), and Lilly and Klemp (1979) solved the non-linear governing equations for orographic blocking by obstacles of certain shapes. From these studies, the critical Froude number for a bell-shaped mountain has been found to be 0.85 (Lilly and Klemp, 1979). In addition, Kao (1965) has also carried out a theoretical study of the blocking phenomenon in stratified flows. Kitabayashi (1977) and Baines (1979) have studied the blocking through both field and laboratory studies. Mannis and Sawford (1982) have carried out blocking studies in valleys through field experiments, and the results were consistent with the laboratory studies of Bell and Thompson (1980). From these works, the published values of the critical Froude number \( Fr_c \), lie in the range 0.5 to 2.3, consistent with the heuristic order-of-magnitude estimate \( Fr \sim 1 \). These values have been used by Bell and Bosart (1988) in discussing Appalachian cold air damming. Davies (1984) also discussed orographic retardation through a theoretical model and found that the slope of the blocked front is characterized by the rotational Froude number. However, the model is somewhat theoretical and simplified, and is not immediately relevant for practical applications.

It should therefore be fruitful to study the Froude number in relation to the blocking of cold surges in southern China. Cheng (1994), in a study of about 10 events, has found that the Froude number is a useful index for predicting the arrival the northerly cold surges. He concluded that the critical Froude number was within the range 0.89 to 1.23 - when \( Fr > 1.23 \), cold surges would reach the coast of south China (including Hong Kong) within 12-24 hours, but if \( Fr < 0.89 \), no drastic drop in temperature would be experienced. Froude numbers in the range 0.89 to 1.23 appeared to lead to indeterminacy. Thus there are two issues. First, there is a spread in the \( Fr \) values among different locations. This spread is large, e.g., the range 0.5 to 2.3 quoted in the literature. This is attributable, at least in part, to the differing assumptions and shapes of the barriers, as well as definitional conventions. For a specific geometry at a particular location, and under a consistent convention, it should be possible to define a more precise \( Fr \) as a
forecast index. Secondly, it appears that even for a particular location, Fr alone may not be adequate in giving an unambiguous signal, e.g., events with Fr in the range 0.89 to 1.23 in the study of Cheng (1994). Thus other supplementary parameters may have to be introduced as well. Our intention is to remedy both of these defects in the context of southern China.

In this work, we consider a larger sample of northerly cold surges and try to pin down a more accurate value for Fr to describe orographic blocking of cold surges by the Nanling Range. First, we consider a sample using ECMWF data, from which fairly clear conclusions can be drawn. However, this result is not immediately useful to forecasters, since the ECMWF data set, though systematic, is not available in real time. Therefore we also consider a sample based directly on primary data from meteorological stations. Though conceptually the same, the latter approach is likely to have practical utility.

Secondly, we find that even though Fr is now much better specified, there is still a degree of indeterminacy. We demonstrate that the simultaneous use of a pair of indices, involving both Fr and a certain geopotential height difference ΔZ, can lead to essentially unique and reliable predictions.

The rest of this paper is organized as follows. The sample of northerly cold surges considered in this study are defined in Section 2.1. The methods of calculations using the ECMWF data and the meteorological stations data are respectively described in Sections 2.2 and 2.3, and the two are compared in Section 2.4. The definition of the geopotential height difference ΔZ is given in Section 2.5. Results and discussions are presented in Section 3, including the use of ΔZ as a supplementary index. The conclusion is given in Section 4.

Methodology

2.1 Definition of sample

Samples are taken in the months of December, January and February over the period January 1986 to December 1993. (January 1987, December 1991 and February 1992 are excluded because the data sets are not available). An event is included in the sample if Δρ > 7 hPa; this criterion follows that of Lai (1989) for classifying an event as a potential cold surge and placing it under scrutiny. There are about 30 such events within the period under consideration. This allows a more detailed analysis of the statistics than was possible with the more limited sample of Cheng (1994).

For each event in the sample, two parameters are then obtained. First, the Froude number Fr is calculated (using either ECMWF or meteorological station data) in the manner specified below. Secondly, each event is labelled as "successful" or "unsuccessful" according to the following criterion. A surge is "successful" if either there is a temperature drop in Hong Kong of 3°C or more within the next 12 - 36 hours, or if the prevailing wind in Hong Kong shifts to the direction from 330° and 030° with mean speed of at least 5 ms⁻¹, again within the next 12-36 hours. The two criteria are consistent with the classification of cold surges into temperature surges and wind surges (Lam, 1976).

The objective is to see whether, within such a sample, "success" correlates with the value of Fr.

2.2 Calculation of Froude number using ECMWF data

The ECMWF data set supplied by ROHK refers to 0000 UTC and 1200 UTC. The data set is first interpolated from the 2.5° x 2.5° resolution to a 0.5° x 0.5° grid. We then compute the Froude number as follows. First, the flow characteristics (i.e., the velocity U and the frequency N) are evaluated at each of the 13 grid points along 28°N from 110°E to 116°E, as follows. Here, U the northerly component of the velocity field averaged over the 850 hPa and the 1000 hPa levels, and N is calculated from (1) by using the difference in potential temperatures between these two levels. The terrain data (i.e., the heights H) are evaluated at the corresponding points on 25°N, which is the approximate position of the Nanling. The original terrain data set of resolution 1/6° is also interpolated to the same grid structure to give the barrier heights H at each of these grid points. Because the Nanling is far from uniform, these values of H range from 263 m to 876 m. Finally, the computed Froude numbers at these 13 grid points are averaged.

2.3 Calculation of Froude number using the meteorological station data

In order to put the Froude number statistics to practical use, a corresponding analysis needs to be performed using the meteorological station data, taken from the actual synoptic charts stored as microfiches in ROHK. Two meteorological stations close to latitude 28°N and due north to northeast of Hong Kong are considered (Fig. 3).
A. Changsha (57687 (surface), 57679): 112.59°E, 28.09°N

B. Nanchang (58606): 115.57°E, 28.37°N

These lie very close to the area specified by the 13 grid points in the ECMWF analysis.

At these stations, both surface and 850 hPa meteorological elements (wind speed in knots, wind direction, temperature, mean sea level pressure, geopotential height, etc.) are available at 0000 UTC and 1200 UTC (Hong Kong time 8 a.m. and 8 p.m. respectively). The Froude number for each of these stations is then calculated from the station data. In this case, \( U \) is the northerly component of surface wind, rather than the average at 1000 hPa and 850 hPa. The latter is not used for two reasons. First, the wind speed at 850 hPa is often unavailable. Secondly, there is significant local variation of wind speeds at 850 hPa along the horizontal directions, rendering the local samplings less useful than the smoothed data provided by ECMWF. The frequency \( N \) is calculated from the temperature records on the surface and on the 830 hPa level using (1). Since we are concerned with one given barrier, the value of \( H \) is a constant over all events, and can be dropped from the analysis, i.e., we could deal directly with the ratio \( U/N \). However, it will be convenient to normalize these ratios by a nominal value \( H \) in order to obtain a dimensionless parameter that can be interpretable as a Froude number. From the definition of \( Fr \), it seems reasonable to take \( H \) as the harmonic mean of the terrain heights, i.e., to emphasize the smaller values of \( H \). This is also not unreasonable since cold surges tend to pass over the gaps in the barrier. With these considerations in mind, the data presented below have been normalized by using the arbitrary choice \( H = 300 \) m. This is nothing more than a convention, and does not affect the substance of the analysis.

After the Froude number for each station has been calculated, the larger value of the two will be adopted as the forecasting index.

2.4 Comparison between ECMWF and station data

If the Froude number calculated from the ECMWF data and from the station data are compared event by event, it is found that the former is typically twice as large.

We have examined the source of this discrepancy, by analysing the factors \( U \), \( N \) and \( H \) in each case.

The wind speed \( U \) from the ECMWF data tends to be slightly larger because it is an average of 850 hPa and 1000 hPa values, whereas for the station data we have taken only the surface values. However, the largest source of discrepancy are differences between the lapse rates reported by the stations and those extracted from the ECMWF data, leading to significant differences in \( N \). The different conventions for the definition of \( H \) can also contribute a multiplicative factor between the two sets of data.

It is not our task here to try to understand these differences, or argue which is more reliable. The difference does not affect the search for a critical value of \( Fr \). For this purpose, it will not matter at all if any one set has a constant multiplicative error, and this will be accepted in the rest of this paper.

2.5 Geopotential height difference

As will be explained in Section 3, the north-south geopotential gradient on 850 hPa will also be an important parameter; in practice, the geopotential height difference \( \Delta Z \) between two points separated in the north-south direction can be used as a proxy for the gradient.

For the ECMWF data, we take \( \Delta Z \) to be

\[
\Delta Z = Z(28) - Z(25.5)
\]

where \( Z(28) \) and \( Z(25.5) \) are respectively the geopotential heights on latitudes 28° 25.5°N, averaged over the same longitude range as mentioned earlier.

For the station data, in addition to Changsha (57687) and Nanchang (58606), two other stations in the vicinity of Nanling Range are considered (Figure 3).

C. Chenzhou (57972): 113.00°E; 25.45°N

D. Ganzhou (57993): 114.50°E; 25.49°N

The geopotential height differences on 850 hPa of the two pairs (57679, 57972) and (58606, 57993) are calculated.
3. Results

3.1 Froude number statistics using ECMWF data

The cold surge event occurring over the period 8 to 14 January 1989 exemplifies the extra information provided by the Froude number $Fr$ over $\Delta p$ as a forecasting tool. The synoptic background is discussed in detail in Cheng (1994), and will not be repeated here. Figure 4 shows the time series of $\Delta p$, $Fr$ and the temperatures recorded in Hong Kong from 0000 UTC 08 January 1989 to 1200 UTC 14 January 1989. The temperature record clearly indicates that the surge was initially stationary north of Nanling, but crossed the barrier and arrived in the coastal region on 13 January. The surge was severe; the temperature drop was more than 12°C over the last two days.

First consider the $\Delta p$ trace. The first increase to 8 hPa at about 1200 UTC 8 January can be ignored, since $\Delta p$ did not show a further increase beyond this value. The Froude number was extremely small, and the surge did not "succeed" in the next two days. Then at about 0000 UTC11 January, $\Delta p$ again breached the 8 hPa threshold, and continued to increase significantly. According to the $\Delta p$ forecasting rule, a cold surge would be expected in the coastal region within the next 12 to 24 hours, but the surge became evident only after about 36 hours. Note that at these time, the Froude numbers were relatively low, ranging between 0.3 and 0.7. While $\Delta p$ remained high, the Froude number did not show a substantial rise until about 1200 UTC 12 January, reaching a value of $Fr \approx 1.0$, and staying at that level for 18 hours. The cold surge continued and intensified, with further drops in temperature, culminating in a minimum in early morning of 13 January (0000 UTC 13 January). The contrast between the first two "failures", with $Fr < 0.7$, and the subsequent "success", with $Fr \approx 1.0$, would indicate that $Fr$ should be a valuable indicator in addition to $\Delta p$.

In this event, a relatively large $Fr$ signaled that a cold surge already initiated would continue in strength; in other cases a large value of $Fr$ signals that a cold surge would begin. In any event, we regard the surge as a "success" if, after the $Fr$ signal, the temperature continues to drop and/or the wind directions shifts, in the manner defined.

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The above event is only meant to illustrate some of the important features. To develop a forecasting rule, one needs to study a large sample of representative events. The overall statistics of about 50 potential northerly cold surges, from January 1986 to December 1993, is shown in Figure 5. The dots represent the "successes" while the crosses represent the "failures".

From this chart, the following conclusions can be drawn: (a) for Fr > 0.9, a cold surge will materialize (or continue in strength) south of the Nanling; (b) for Fr < 0.8, the cold surge will be blocked; and (c) in the range 0.8 to 0.9, the Froude number alone would be indeterminate.

We need to compare this result with Cheng (1994). First of all, Cheng's Froude numbers are somewhat larger, because his use of a "smoothed" orography led to nominal terrain heights that were lower than the actual ones. However, this is purely a matter of convention adopted in normalizing the data, and is of no physical significance. The important point is that we have narrowed the indeterminate band.

The analysis in Figure 5 shows that events with Froude numbers in the range 0.8 to 0.9 would be indeterminate on the basis of Fr alone. The event in January 1991, shown in Figure 2, belongs to this category. The Fr trace, similar to the $\Delta p$ trace, shows approximately the same values on 1 January and on 4 January, yet only the second of these led to a significant temperature drop shortly thereafter. The Froude numbers in these two cases were close to the top end of the indeterminate range of 0.8 to 0.9; see data points for 91j in Figure 5.

One can try to use both Fr and $\Delta p$ simultaneously (Figure 6) in order to improve the prediction. We see that "successes" and "failures" are still mixed, and forecasts based on this pair will still contain ambiguities. This plot also shows that Fr is a somewhat better predictor than $\Delta p$.

The indeterminacy is not too surprising since Fr, and also $\Delta p$, only captures the characteristics of the flow in the boundary layer, and external synoptic scale forcing has not been taken into account. Since the top of the boundary layer is approximately at 850 hPa, the geopotential gradient on this level may be taken to be an indicator of the strength of external synoptic scale forcing that acts on the boundary layer. A larger geopotential gradient would help to drive the cold air over the barrier.

Instead of the gradient, we consider the geopotential height difference $\Delta Z$ on 850 hPa
Figure 6  Froude number and the $\Delta p$ distribution for all samples (ECMWF data).

Figure 7  Froude number Fr and geopotential height difference $\Delta Z$ on 850 hPa level distribution for all samples (ECMWF data).
between 28°N and 25.5°N, along the same longitude range mentioned in the previous section, taken from the interpolated ECMWF data set.

Figure 7 shows the events in the sample on a plot of $Fr$ and $\Delta Z$. There is a remarkable clear-cut separation between the “successful” and the “unsuccessful” surges, shown by the dashed line. Moreover, neither $Fr$ nor $\Delta Z$ alone would have given a clear-cut separation.

Thus, this method resolves the ambiguity for Froude numbers lying in the mixed region 0.8 to 0.9, and the pair $Fr$ and $\Delta Z$ can be used as a predictor for the passage of cold surges over the Nanling Range.

3.2 Froude number statistics using meteorological station data

The ECMWF data, though systematic, are not available in real time. So for operational forecasting, it is necessary to adapt the above results to meteorological station data. The definition of $Fr$ and $\Delta Z$ in terms of station data has been discussed in Section 2.

Figure 8 shows the station values of Froude numbers for the sample. Again there is a good separation: surges with $Fr > 0.63$ “succeed”; whereas those with $Fr < 0.35$ “fail”, the intermediate range 0.35 to 0.63 is indeterminate. The indeterminate band is broader, in part because station data are more “noisy”.

Next, the station Froude numbers $Fr$ and the corresponding geopotential height differences $\Delta Z$ of all sample surges are plotted in Figure 9. Recall that only the larger Froude number from the two stations is used, and the $\Delta Z$ value is taken from the north-south difference of the corresponding pair. There is again a clear-cut separation between the “successful” and “unsuccessful” surges, as shown by the dashed line. The clear separation is all the more remarkable given that station data are expected to be somewhat “noisy”. This then provides a practical forecasting guide.

4. Conclusion

In this statistical study, we have shown that the Froude number $Fr$ is useful in predicting the passage of cold surges over the Nanling; when coupled with $\Delta Z$, the prediction becomes accurate and unambiguous. This scheme works both with the ECMWF data and also the meteorological station data; the latter is all the more remarkable on account of possible “noise”.

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We do not imply that $\Delta p$ is not useful, or that it should be abandoned. First, the condition $\Delta p > 7$ hPa remains as the primary signal for an event to be placed under consideration. Moreover, $\Delta p$ is available 6-hourly (pressures being available 3-hourly in Hong Kong but often only 6-hourly from station 57972), and could give more lead time than $Fr$ and $\Delta Z$, which are available only at 0000 UTC and 1200 UTC. Thus the actual forecast guide should rely on all three parameters: $\Delta p$, $Fr$ and $\Delta Z$.

It is perhaps not surprising that the three together should be so useful. The surface pressure gradient measures the forcing within the boundary layer, $\Delta Z$ measures the synoptic scale forcing above the boundary layer, while $Fr$ indicates the ability to climb over the physical terrain barrier. It would be interesting to attempt actual forecasts with this methodology.

**Acknowledgement**

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IPCC Rome Plenary Finalizes Second Assessment Report

- Narasimhan Sundararaman, Secretary, Intergovernmental Panel on Climate Change (IPCC)

The full plenary of the Intergovernmental Panel on Climate Change (IPCC) met in Rome at the invitation of the Italian Ministry of the Environment from 11-15 December 1995 and finalized the 1995 IPCC Second Assessment report for publication. Participants included some 300 scientists, experts, and government representatives from over 120 countries.

Synthesis and summaries

The plenary reviewed and approved the 1995 IPCC Synthesis. The Synthesis is a 11,000-word document that brings together the scientific, technical and socio-economic analyses in the Second Assessment Report relevant to interpreting Article 2 of the United Nations Framework Convention on Climate Change.

Article 2 contains the Convention’s ultimate objective, which is “to achieve stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time-frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner.”

The plenary also reviewed and accepted the contributions of the IPCC’s three working groups, including their Summaries for Policy-makers to the Second Assessment Report. The Working Groups had adopted their respective summaries and contributions at earlier meetings. Working Group I assessed the current scientific understanding of climate change, particularly the effect of human activities. Working Group II explored the environmental and socio-economic impacts of climate change, as well as response options for reducing net greenhouse gas emissions and for managing the impacts of climate change. Working Group III made a technical assessment of information related to the economic and social dimensions of climate change.

How to order

The full Second Assessment Report therefore comprises the Synthesis, three Summaries for Policy-makers, plus three full-length volumes, some 2,000 pages and 10,000 references in all.
Around 2,000 scientists and experts world-wide contributed to the writing and reviewing of the Report.

The three contributions of the IPCC working groups to the Second Assessment Report will be available in early 1996 from Cambridge University Press. A volume containing the Synthesis and the three Summaries for Policy-makers will be published by the IPCC Secretariat. The Synthesis, the Summaries for Policy-makers, and ordering information for the print version will be posted on the Internet at the following web sites:

http://www.unep.ch/ipcc/ipcc-0.html and

http://www.wmo.ch.

For additional information on ordering, please contact the IPCC Secretariat, c/o WMO, C.P. 2300, 1211 Geneva 2, Switzerland.

TRAIN Phase II to Focus on National Communications

- Gao Pronove, Programme Manager, United Nations Institute for Training and Research (UNITAR), and Silke Speier, Research Associate, CC:TRAIN Programme.

The CC:TRAIN programme was launched in 1993 to promote the long-term implementation of the Climate Change Convention by developing countries. By focusing on education and the training of national policy-makers and other stakeholders, the programme aims to maximise public involvement in realizing the Convention's goals. It also seeks to strengthen institutions and to build capacity for preparing the national communications that developing countries must submit to the Conference of the Parties to the Convention.

CC:TRAIN is funded primarily by the Global Environment Facility (GEF) and is executed by UNITAR, which works closely with the Convention Secretariat, the UN Development Programme, and the Information Unit on Climate Change. Its activities are carried out by country teams supported by a regional network of partner institutions. CC:TRAIN has now completed its two-year pilot phase and is starting a new three-year phase, Phase II.

The pilot phase helped to establish country teams composed of people from many different sectors and disciplines. The role of these teams is to lead the policy dialogue needed for developing a national implementation strategy. The pilot phase also produced a CC:TRAIN Workshop Package. This package contains extensive material and will be used as a training tool to enable the country teams and others to run workshops on climate change and the Convention.

While the pilot phase concentrated on three countries -- Lithuania, Vietnam, and Zimbabwe -- Phase II will include 18. They are Benin, Chad, Nigeria, and Senegal in Africa; Bolivia, Cuba, Ecuador, Paraguay, and Peru in Latin America; and the Cook Islands, Fiji, Kiribati, Marshall Islands, Nauru, Samoa, Solomon Islands, Tuvalu, and Vanuatu in the Pacific region.

In addition to expanding the range of countries, the second phase will move beyond sensitizing people and promoting dialogue to providing practical assistance for carrying out a key Convention obligation -- producing national communications. Developing countries must submit their first communications within three years of becoming a Party. (Least developed countries may make their initial communication at their discretion.) These communications should include a national inventory of greenhouse gas emissions, a general description of steps taken or planned to implement the Convention, and any other information that the Party considers relevant.

The challenge for many countries is that their institutional framework for implementing the Convention is not obvious. There is also a lack of awareness among policy-makers about the issue. Preparing a national communication, of course, demands technical knowledge as well as adequate information about climate change and policy options. It requires articulating the benefits to the country of carrying out its treaty commitments, identifying sources of support (both local and external), and mobilising people from within the government and other sectors.

Country teams

To help governments meet the challenge of formulating their communications, Phase II will adopt both a country team approach and a regional approach.

Each country team will be housed by a host agency designated by the government. The team will include national experts from various government agencies, industry, NGOs, and the research and academic community. It will be responsible for organizing the CC:TRAIN
activities and preparing country studies, the national implementation strategy, and the national communications.

The CC:TRAIN programme will offer country teams the resources and training they need (in English, French, or Spanish) for undertaking the required activities and tasks. In addition, regional networks of partners will be created to deliver programme support, training, and technical assistance to participating countries in that region. This should ensure that the technical assistance provided is relevant, cost-effective, and timely. Each regional network will also be available to aid other projects and programmes designed to help countries formulate their initial communications. In this way, countries not included in phase II will nevertheless be able to start using the services and materials developed for CC:TRAIN. These regional partner institutions will be established in early 1996.

By mid-1996, a calendar of training workshops will be established for each region. These workshops will address the issues of preparing national greenhouse gas inventories, assessing vulnerability and adaptation, and analysing mitigation options. They will be organized by the regional partners in cooperation with other institutions and will be open to participants from other countries.

Watch this space

The CC:TRAIN programme plans to promote communication amongst CC:TRAIN focal points through the UN Climate Change Bulletin. In addition to updates on the progress of Phase II, it will publish announcements of workshops and other activities plus substantive articles by authors from CC:TRAIN participating countries. Comments from readers are welcome.

For further information, please contact Gao Pronove, CC:TRAIN Programme Manager, UNITAR, Palais des Nations, 1211 Geneva, Switzerland; tel: +41 22 788-1417 or 979-9483, fax: +41 22 733-1383, email: gpronove.unfccC@unep.ch

CC:TRAIN's six components

The country team approach and the regional approach are built into the following six steps for achieving CC:TRAIN's immediate objectives.

1. Establish a network of regional partners
2. Establish a country team
3. Facilitate a process for developing national policies
4. Plan and undertake country studies
5. Prepare the national strategy for implementation and the national communication
6. Share CC:TRAIN resources with global partners

Convention Parties Start Work on Future Commitments

- Michael Zammit Cutajar, Executive Secretary, Climate Change Convention

The new "process" launched by the Berlin Mandate is just beginning, but already one can see the outlines of the difficult debate that lies ahead. If anything, the discussions on stronger commitments for developed countries will prove more challenging than the original Convention negotiations. There are several reasons for this.

First, the idea of an overall target for emissions levels -- also a key element in the Convention talks -- is joined now by the idea of achieving emissions reductions through coordinated policies and measures. This new focus on specifics such as standards, taxes, and regulations introduces a new complexity. It also involves real and identifiable consequences for real and identifiable groups. More broadly, it raises the prospect of new commitments that could significantly affect trade and investment.

Second, most developed country Parties do not seem to be on track to achieving their current aim of returning greenhouse gas emissions to 1990 levels by the year 2000. At the same time, their legislatures and electorates are deeply concerned about short-term economic growth and economic deregulation. The climate change issue is not yet at the top of their agenda.

This may change. The new assessment report from the Intergovernmental Panel on Climate Change (IPCC) reveals that scientific uncertainty -- a major barrier to action -- is being steadily reduced. The report goes further than ever before by stating that scientists now believe that "the balance of evidence suggests a discernible human influence on global climate." This significant conclusion will certainly contribute to mobilizing political support for stronger commitments.

The Berlin Mandate (4GBM)

Since the First Session of the Conference of the Parties (COP-1) in Berlin last March, the
Convention process has moved to a new rhythm. Until Berlin, discussions were carried out by a Committee whose two working groups met concurrently for two-week sessions about thrice a year. Now the COP meets once a year, and the intersessional work is carried out by four subsidiary bodies.

All four bodies have held their first sessions and organized their work. While each body has its own dynamics, their work streams intermingle and are fully coordinated by the COP Bureau. Together they will hold about 10 meetings before reporting on their progress at COP-2, to be held in Geneva from 8 - 19 July 1996.

The ad hoc Group on the Berlin Mandate (AGBM) was established by COP-1 to carry out a "process to enable governments to take appropriate action for the period beyond 2000, including a strengthening of developed country commitments, through the adoption of a protocol or another legal instrument". It was agreed that the AGBM's work should be completed as early as possible so that the results can be adopted at COP-3 in 1997.

The AGBM met for the first time from 21-25 August. With Ambassador Razl Estrada-Oyuela of Argentina in the Chair, the AGBM agreed on a schedule and an approach to its work for the next two years. The second meeting (AGBM-2), held from 30 October to 3 November, pushed the process forward by getting the substantive options and issues for future debate out on the table.

This meeting launched the "analysis and assessment" of "policies and measures" that developed countries could adopt after the year 2000 in order to limit emissions and protect carbon "sinks" and "reservoirs" (such as forests). These policies and measures could be included in the future legal instrument.

The participants acknowledged the wide range of possible policies and measures, and they agreed to continue analysing and assessing them in order to produce a more definitive list. However, while some countries prefer to continue with an in-depth study of all options, others would rather move more quickly into negotiating specific commitments.

The emerging priorities among policies and measures reflect a preference for controlling emissions through technological solutions (rather than changed consumption patterns). A technological strategy for emissions limitation implies giving some sort of guidance to the market to generate and encourage the technologies needed. This in turn implies that Parties should adopt common policies and measures and implement them in a coordinated manner.

**Possible objectives**

AGBM-2 also considered possible objectives for the protocol. The Berlin Mandate calls for setting "quantified limitation and reduction objectives within specified time-frames, such as 2005, 2010 and 2020", for greenhouse gas emissions by developed countries. Some countries, including those with economies in transition, have raised the issue of having differentiated objectives for different groups of developed countries.

Together with the work on policies and measures, progress on how to formulate the objectives will enable Parties to start considering the protocol's ultimate form and content. Discussions were in fact initiated on how to structure a protocol. The European Union tabled a draft protocol outline, which now joins company with an earlier draft protocol proposed by the Association of Small Island States (AOSIS).

While the Berlin Mandate process will not consider new commitments for developing countries, the meeting did consider how to continue advancing the implementation of the existing general commitments that both developed and developing countries have under the Convention. In this context the Group of 77 and China will convene a forum for sharing experiences on the national communications that developing countries will start submitting in March 1997. One concern of many developing countries is that sufficient funds for producing these communications be made available in time.

The AGBM will next meet from 5-8 March 1996. It will consider, among other topics, the relevant aspects of the IPCC's Second Assessment Report and a new report on innovative and efficient technologies and know-how. In addition, failure to agree on the structure of the AGBM's bureau means that this procedural issue remains on the agenda.

**SBSTA and SBI**

The Subsidiary Body for Scientific and Technological Advice is (together with SBI) one of two permanent subsidiary bodies established by the Convention (AGBM and AG13 were established by the COP). Its role is to serve as the link between the information and assessments provided by expert sources on the one hand, and the policy-oriented needs of the COP on the other hand.
other. The SBSTA will achieve its maximum potential if can operate as a non-politicized group of experts.

The first meeting, from 28-30 August, elected officers, including Tibor Farag of Hungary as Chairman. It was dedicated primarily to setting out a work programme through 1997 and identifying what inputs are desired from the IPCC. However, the group failed to agree on the structure and membership of the technical advisory panels (TAPs) that are to support its work.

Among other activities, the SBSTA will soon start discussing the guidelines to be used by the developing countries in preparing their first national communications. It will also conduct an inventory of available technologies that will be a valuable input for the AGBM. The next meeting will be held from 27 February - 4 March 1996.

The Subsidiary Body on Implementation (SBI), whose role is to assist the COP in assessing and reviewing the Convention’s implementation, met from 31 August to 1 September. It addressed organizational, institutional, and budgetary matters. It elected officers, including Chairman Mohamed M. Ould El Ghouth of Mauritania.

The SBI also considered a draft memorandum of understanding between the COP and the Council of the Global Environment Facility (GEF), which is the interim operating entity for the Convention’s financial mechanism. The SBI recommended that COP-2 adopt the memorandum and accept the working relationship that it outlines between the two organizations. The next meeting will be from 27 February - 4 March.

Article 13 (AG13)

The ad hoc Group on Article 13 (AG13) has met once, from 30-31 October. This Group was set up in response to Article 13 of the Convention, which calls on the Parties to “consider the establishment of a multilateral consultative process for resolution of questions regarding the implementation of the Convention.” The Chair is Mr. Patrick Szell of the UK.

This first meeting of experts considered possible approaches to its task. Article 13 could provide innovative tools for assisting the implementation of the Convention. In order to identify all the options, the meeting drafted a questionnaire for distribution to Parties and observers. The Group agreed to reconvene in July 1996.

Towards COP-2

The post-Berlin process is in many ways a new beginning. As in the early days of the Convention negotiations, back in 1991 and 1992, these first meetings are witnessing a good deal of procedural work, exploration, and tactical positioning. But just as the Framework Convention was drafted under the pressure of an Earth Summit deadline, the Berlin Mandate process too faces a tight schedule -- it must be completed by COP-3 in 1997.

The work pace must therefore remain steady if the implementation of existing commitments and the elaboration of new ones is to remain on track. In July 1996, just six months from now, COP-2 in Geneva will offer a vital midway mark for measuring the Berlin Mandate’s vitality.

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OECD Research Update:
Annex I Expert Group and GHG Inventories

- Jan Corfee-Morlot, Bo Lim and Fiona Mullins, OECD Environment Directorate

The Organisation for Economic Co-operation and Development (OECD) has actively contributed to the climate change policy debate since 1991. It has also addressed a wide range of technical issues. For example, the OECD Secretariat has published extensively on the “cost” of responding to climate change over different time periods and with different emissions constraints. It has also studied economic instruments and benefits to inform member countries about the range of available policy response options and their likely effects.

Less well known is the work that the OECD has undertaken with the International Energy Agency (IEA) and with other intergovernmental organisations to promote the implementation of the Convention. The two main strands of this work are the IPCC/IEA/OECD Programme on National Greenhouse Gas (GHG) Inventories, and the Annex I Expert Group on the Climate Change Convention.

These activities are noteworthy for at least two reasons. First, they take a highly practical approach to designing products that can help all Parties to implement the Convention. Second, they are managed by, and aim to influence, a much wider audience than the OECD members.
National GHG Inventories

Under the Convention, each Party must regularly submit "national communications", including a national GHG inventory. A GHG inventory lists the quantities of each greenhouse gas that are emitted by various sources (e.g. transport or agriculture) or removed by various sinks (e.g. forests). In order to make the various national inventories comparable, it is necessary to use consistent methodologies and common reporting formats.

Between 1991 and 1994, the Intergovernmental Panel on Climate Change (IPCC), the OECD, and the IEA collaborated on the IPCC Guidelines for National Greenhouse Gas Inventories. Over 600 copies have been distributed or sold worldwide in English, French, and Spanish (and soon in Russian). Some 60 countries have used the IPCC methodology for their GHG inventories, including China, India, and Russia. Software is distributed by the OECD upon request and may soon be available on the internet.

Phase II of the inventory programme was launched in 1995. This new phase is focusing on methods development, technical outreach, and the transfer of operational activities from the IPCC to the Convention’s Subsidiary Body for Scientific and Technical Advice (SBSTA). The purpose of methods development is to ensure that the IPCC Guidelines reflect the most current scientific knowledge for all major anthropogenic sources and sinks of GHGs. It also ensures that they can be systematically applied to all regions of the world in order generate high-quality emission data.

To achieve these objectives, five expert groups containing over 130 specialists are addressing key methodological issues in the areas of industrial processes and "new gases" (PFCs, SF6, HFCs) fuel combustion, agricultural soils, land-use change and forestry, and waste. The five groups and their expected products are summarised in Table 1.

Expert Group recommendations for the IPCC Guidelines (methodologies) will be discussed at a workshop to be held in December on Greenhouse Gas Emission from Agricultural Soils, Industrial Processes and Waste. A second Workshop will be held in February or March on Land Use Change and Forestry and Fuel Combustion.

In addition, the IPCC/IEA/IPCC team is performing an in-house analysis of Annex I country inventories. (Annex I to the Convention is a list of 24 OECD members and 12 countries with economies in transition who have additional treaty commitments). It will also draw upon results from similar US and UNEP country studies of national inventories in South America, Southern Africa, Asia, and Eastern Europe. This review will identify new sources of data and suggestions for improving the Guidelines.

Phase II is currently scheduled to continue until April 1996. If the IPCC approves the extension for Phase II at its December 1995 Plenary, the expert groups’ recommendations will be subjected to an international IPCC peer review. Once endorsed by the IPCC and cleared by the Convention’s subsidiary bodies, the final recommendations will be presented for consideration to the Conference of Parties of the Convention.

Annex I Expert Group

Another activity of the OECD is its support for the Annex I Expert Group, which was established in 1993 at the request of OECD Member countries. It is an ad-hoc group operating in association with the OECD Environment Policy Committee. Its work programme, operated jointly with IEA since 1994, is principally supported by grants from Member countries.

The Group’s earlier products included recommendations on the content and format of the first national communications from Annex I Parties and on the first review of national communications from Annex I Parties. (In addition to the GHG inventories, these national communications include a description of policies and measures to limit greenhouse gas emissions, a projection of how these measures will affect future emissions, and a description of educational, research, and other activities). The present purpose of the Annex I Expert Group is to analyse key issues -- it does not act as a negotiating forum for Annex I Parties or prejudge nations’ preferences. It provides inputs for consideration by the Convention’s subsidiary bodies, particularly the ad-hoc Group on the Berlin Mandate (AGBM).

In response to the Berlin Mandate, which launches negotiations for new developed-country commitments in the post-2000 period, the OECD and the IEA asked the Annex I Expert Group to work on issues related to possible future commitments. The new work programme focuses initially on policies and measures for common action and on methodologies for projecting emissions and estimating the effects of various measures.
The overall objective of the Project on Policies and Measures for Common Action is to broadly assess the relative potential of a range of policies and measures for common action by Annex 1 Parties. At its September meeting, the Group considered over 100 measures and selected around a dozen for further study. The selected measures cover the energy supply, transport, energy end use, and agriculture and forestry sectors, and include a range of voluntary, regulatory, financial and economic instruments. All greenhouse gases are considered.

More recently, at its November meeting, the Group also prioritised measures for analysis and assessment; approved a budget; and agreed on a schedule for the analysis.

Progress to date includes the development of an initial study and three pilot case studies. The Project has also developed a draft framework for the analysis and assessment of policies and measures. This framework identifies a range of issues for analysis in the study of each policy or measure. It was recently submitted to the AGBM. The analysis of policies and measures will proceed in two tranches (see Table 2). The first tranche is designed to produce a set of studies for the second session of the Conference of the Parties (COP-2) in July 1996. The analysis is to begin immediately, subject to the availability of grant funding. The second tranche of work would begin in early 1996 and would aim to complete a second set of studies sometime after COP-2.

The Group also endorsed a methodologies project which aims to produce a paper in early 1996 summarising key issues in projecting GHG emissions and estimating the effects of measures.

For more information on national GHG inventories, contact Bo Lim, Environment Directorate, OECD Tel: (33.1) 45.24.78.94, Fax: (33.1) 45.24.78.76, Email: Bo.Lim@OECD.ORG

**Table 1: Expert Groups and Expected Products**

<table>
<thead>
<tr>
<th>Expert group</th>
<th>Expected products</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel Combustion</td>
<td>Investigate a method for non-CO2 gases using a bottom-up approach; Review of emission factors for mobile and stationary sources; Review of CO, reference method.</td>
</tr>
<tr>
<td>Industrial Processes and New Gases</td>
<td>New method for fluorinated gases (PFCs, HFCs, SF6) and for CO2 from metal and carbide production; Additional methods for ozone precursors (NMVOC, CO), N2O and CO, from industrial processes and SOx from fuel combustion.</td>
</tr>
<tr>
<td>Land Use Change and Forestry</td>
<td>New method for wood products; Review of land cover classification and biomass default data; Guidelines on the use of remote sensing, possible inclusion of particulates and other non-CO2 gases from biomass burning.</td>
</tr>
<tr>
<td>Waste</td>
<td>Review of CH4 emission data for landfills (including open dumps) and wastewater; Incorporation of time release function into the current CH4 methodology for landfills.</td>
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</tbody>
</table>

**Table 2: List of policies and measures for the "Common Action" study, Annex I Expert Group on the FCCC**

<table>
<thead>
<tr>
<th>Expert Group on the FCCC</th>
<th>Tranche I</th>
<th>Tranche II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sustainable transport issues</td>
<td>CO2 emissions from vehicles</td>
<td>Infrastructure Other issues</td>
</tr>
<tr>
<td>Energy market reform</td>
<td>Market barriers Penetration of market access renewables including R&amp;D Full cost pricing</td>
<td></td>
</tr>
<tr>
<td>Economic/ fiscal instruments</td>
<td>Subsidies Bunker removal</td>
<td>Taxation fuels (i.e. carbon/energy)</td>
</tr>
</tbody>
</table>

HKMetS BULLETIN Vol. 5, No. 2, 1995
Announcing workshop on NGO inputs

Drawing all stakeholders into the Convention process will help Parties to implement their commitments more effectively and to elaborate policies and measures. The International Academy of the Environment, with guidance from the Convention Secretariat, will therefore convene a workshop focusing on mechanisms to develop and strengthen arrangements between and among Parties and environmental organizations, business, and local authorities.

The workshop will take place on 2 March 1996 at the Palais des Nations in Geneva, Switzerland. For more information, please contact Mr. Kevin Hill, UNFCCC Secretariat, tel. (41-22) 979 9319, fax (41-22) 979 9034, or e-mail secretariat.unfccc@unep.ch.

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Protecting the Atmosphere:
A post-Rio checkup

- Alex Alusa, Climate Unit,
United Nations Environment Programme (UNEP)

Three and a half years after UNCED, it is instructive to reflect on what was agreed and what has been achieved so far. As the task master for Chapter 9 of Agenda 21 -- "Protection of the Atmosphere" -- UNEP will submit such an analysis to the next meeting of the Commission on Sustainable Development (CSD). This article summarizes some of our key findings concerning climate change.

Chapter 9 contains four programme areas. While two of them -- transboundary atmospheric pollution, and preventing stratospheric ozone depletion -- are not directly linked to climate change, the following two are:

* Addressing the uncertainties: improving the scientific basis for decision-making; and
* Promoting sustainable development: (i) energy development, efficiency, and consumption; (ii) transportation; (iii) industrial development; and (iv) terrestrial and marine resource development and land use.

Improving the science

The complexity of climate dynamics, and the fact that the impacts of today's emissions are only felt in the future but once started can persist for a long time, present a major challenge to those providing information to decision-makers about climate change.

For all atmospheric issues, environmental effects result from the accumulation of pollutants or gases over many decades. In some cases the effects can persist for many decades to millennia even after corrective measures are taken. Projecting how this will impact human society and ecosystems requires an extensive understanding of the global geosphere and biosphere.

This means that policy-makers need credible long-term projections of potential impacts so that they can take action early enough to avoid environmental harm that may be, for all practical purposes, irreversible. Furthermore, detailed and complex information must be condensed, simplified, and transmitted to policy-makers in a form that facilitates decision-making without seeming to dictate policy which, in the end, must be based on value judgments.

These difficulties notwithstanding, there has been steady progress over the past several years towards an improved basis for policy decisions, particularly in the areas of ozone depletion and global climate change. National research programmes have provided a better understanding of atmospheric processes and the impact of
human activities on the atmospheric environment. These programmes are also shedding new light on how an altered atmosphere may affect people and their environment.

At the same time, international assessments of this improved knowledge base are helping to promote an international consensus for action. In particular, the ongoing assessments by the WMO/UNEP Intergovernmental Panel on Climate Change (IPCC) have provided consensus reports from the world's leading experts on all aspects of global climate change. The IPCC assessments cover atmospheric science, impacts, adaptation and mitigation options, technology opportunities, and social and economic implications. This comprehensive coverage provides a strong basis for informed decision-making. IPCC assessments have helped underpin the recent agreement that there is a need for further measures beyond the commitments already contained in the Climate Change Convention. Equally important, they have focused the attention of the scientific and technical community on decision-makers' need for even more rapid progress in reducing uncertainties.

The IPCC assessments also contribute to building scientific and technical expertise in developing countries. Nevertheless, the level of scientific and technical expertise in developing countries for protecting the environment is far from satisfactory. Building capacity in developing countries should therefore remain a priority issue in the coming years.

The focus on policy-maker requirements should also remain a priority. Continued progress in reducing uncertainties will increasingly involve better information in the areas of impacts and the social sciences. Unfortunately, these areas are grossly underfunded at the national level and there is inadequate coordination of activities at the international level.

Promoting sustainable development

As described in Agenda 21, activities for addressing global climate change are central to sustainable development. Progress in this area has been made at both within countries and internationally. The Climate Change Convention has been ratified by 145 countries, and a growing number of those countries have developed national action plans for implementing their commitments.

Most significantly, there is general agreement among the Parties to the Convention that further measures will be required to achieve its ultimate objective. This resulted in the Berlin Mandate of March 1995 launching a process aimed at strengthening developed country commitments through a protocol or other legal instrument. The results of this process are scheduled for adoption at the third session of the Conference of the Parties in 1997. Thus, there is a trend of increasing commitment to action.

However, atmospheric concentrations and emissions of the major greenhouse gases continue to grow. Projections suggest that, in the absence of a concerted international effort, they will continue to increase, committing us to an essentially irreversible global environmental change -- with no clear understanding of the consequences.

Scientific uncertainty and the link between improved living standards and greenhouse gas emissions are the primary impediments to action. Stronger commitments to research and develop new energy sources and to improve energy efficiency could decouple living standards from greenhouse gas emissions and thus remove one major obstacle.

Next steps

Looking back at Rio from today's vantage point, it is clear that some progress has been achieved. However, there are 3 areas that require much more attention by the international community.

First, developing countries need further assistance and encouragement to contribute to the protection of the global climate.

Second, there should be a stronger focus on the linkages between individual issues. For example, many of the activities that involve phasing out ozone-depleting substances also use significant amounts of energy. Some of the CFC substitutes (notably HCFCs) are greenhouse gases. Care must be taken to manage greenhouse gas emissions during the phase-out of the ozone-depleting substances.

Third, increasing attention should be given to tackling environmental problems as resource management issues. Currently most regional and international agreements adopt the more traditional approach of simply avoiding or correcting specific environmental impacts. Both ozone-depleting substances and greenhouse gases, for example, might be managed more effectively as part of the broader issues of industry and of energy production and consumption.

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Convention Calendar 1996

26 Feb, Geneva
Workshop on communications from non-Annex 1 Parties

27 Feb - 4 March, Geneva
SBSTA, second session
SBI, second session

28 Feb (p.m.), Geneva
AGBM Workshop on policies and measures

2 March, Geneva
Workshop on mechanisms for NGO inputs

4 March (p.m.), Geneva
AGBM Workshop on QELROS (quantified emission limitation reduction objectives)

5 - 8 March, Geneva
AGBM, third session

8-19 July, Geneva
COP 2, including:
AGBM, fourth session
SBSTA, third session
SBI, third session
Ad Hoc Group on Article 13 (AG13), second session

For more information, please contact the UNFCCC secretariat at Geneva Executive Center, 11-13 chemin des Animones, 1219 Chatelaine, Switzerland. Tel: (41-22) 979 9111. Fax: (41-22) 979 9034. E-mail: secretariat.unfccc@unep.ch
News andAnnouncements

This section is intended for dissemination of news and announcements by the Society or any of its members. If members wish to relay any news or make any announcement of interest to members which is related to the aims of the Society they should mail or fax such information to the Editor-in-chief along with their name(s) and membership number(s).

WORKSHOP ON WEATHER AND CLIMATE FOR HONG KONG SECONDARY SCHOOL TEACHERS

A Workshop on Weather and Climate for Secondary School Teachers, co-sponsored by the Society and the Department of Physics and Materials Science, City University of Hong Kong will be held at City University of Hong Kong on 20 January 1996. The programme will focus on topics relevant to the syllabus of the Hong Kong Certificate of Education Examination.

Three talks will be given: by Prof. Johnny C.L. Chan of City University of Hong Kong on the basic thermodynamics and dynamics of the atmosphere; by Dr. Bill Kyle of The University of Hong Kong on the general circulation, climate and climate change; and by Mr. C.Y. Lam of the Royal Observatory Hong Kong on interpretation of weather maps with the aid of satellite images. There will also be a session related to accessing weather-related information using the World Wide Web followed by a Discussion and Feedback Session.

For further details please contact the Convener of the Workshop, Mr. C.Y. Lam of the Royal Observatory Hong Kong.

SEVENTH HONG KONG METEOROLOGICAL SOCIETY ANNUAL GENERAL MEETING AND TWELFTH RESEARCH FORUM

The Seventh Annual General Meeting of the Hong Kong Meteorological Society will be held at Royal Observatory Conference Hall on Saturday 23rd March, 1996. The Twelfth Research Forum will also be held on the same day in conjunction with the Annual General Meeting of the Society. Further details of the Annual General Meeting and the Research Forum will be announced via the regular newsletters as they become available.

FORTHCOMING CONFERENCE AND CALL FOR PAPERS

The Third International Conference on East Asia and Western Pacific Meteorology and Climate, sponsored by National Taiwan University and National Central University, Taiwan and co-sponsored by the Hong Kong Meteorological Society and the University Corporation for Atmospheric Research, USA, is being planned to be held in Taiwan in early May, 1996.

The focus of the Conference is on the East Asian monsoon and includes the following topics:

Climate
Large scale monsoon features
Mei-yu related phenomena
Tropical cyclones
South China Sea Monsoon Experiment (SCSMEX) related topics
Other topics related East Asia and Western Pacific weather systems

Papers are being solicited in all the relevant areas mentioned above. The deadline for submission of abstracts is 31 January 1996.

For further information you are requested to contact:

Prof. Johnny Chan,
Dept. of Physics & Materials Science,
City University of Hong Kong,
Tat Chee Avenue, Kowloon.
Tel: 2788 7820 Fax: 2788 7830

Mr. Edwin Lai,
Royal Observatory, Hong Kong,
134A Nathan Road, Kowloon.
Tel: 2926 8474 Fax: 2721 5034

Ms. Olivia Lee,
Royal Observatory, Hong Kong,
134A Nathan Road, Kowloon.
Tel: 2926 8453 Fax: 2721 5034

NATIONAL CLIMATIC DATA CENTER (U.S.) ON-LINE NEWS

The following is a short review of new and recently updated on-line datasets and systems available from NCDC via internet. Some of these are accessible via direct ftp and some via www/mosaic:

For ftp: Address is ftp.ncdc.noaa.gov
Login is ftp or anonymous
Password is your email address

For www: Address is http://www.ncdc.noaa.gov
No login or password needed
Use mouse to click on menu items

New Dataset
World War II Era Summary of Day Data
(in commemoration of 50th anniversary of war's end)
- Ftp directory is /pub/data/ww-ii-data
- 162 non-U.S. stations with many in Pacific and European areas
- 1940-1945 period (varies by station)
- Includes elements such as max/min temperature, precipitation, wind gust, snow depth
- Has 'readme.txt' file with information about data, along with gif file - global plot of station locations

New Dataset
Monthly Precipitation Data for U.S. Cooperative and National Weather Service Sites
- Ftp directory is /pub/data/coop-precip
- Also available via www/mosaic
- Over 8000 stations currently active plus historical data for thousands more currently inactive stations
- 1948-1994 period, with some data as far back as 1900
- Monthly and annual precipitation amounts for all years as available
- Has 'readme.txt' file with all needed information; data files by state + 1 file with complete dataset + 1 file with 1994 data

Updated Dataset
Global Summary of Day Data
- Ftp directory is /pub/data/globalsod
- Also available via www/mosaic
- Over 8000 global stations - good worldwide coverage
- Currently covers January 1994 through February 1995; normally have latest month on line about 1 month after end of data month
- 18 elements included, such as mean temperature, max/min temperature, mean dew point, mean wind speed, precipitation, snow depth
- Recently upgraded to Version 2
- Has 'readme.txt' file with complete explanation of dataset along with gif image of station locations

Updated Dataset
Inventories and Station Lists
- Ftp directory is /pub/data/inventories
- Also available via www/mosaic
- Now has 28 various inventories and station lists
- Includes inventories and station lists for global surface data, NEXRAD data, U.S. cooperative data + the NCDC Products & Services Guide
- Has 'README.TXT' file with complete details (upper-case files)

Updated Dataset
Interactive Visualization of Climatic Data
- Available via www/mosaic
Visualization tools for U.S. climate divisional data + NCDC’s Global Climate Perspectives System
- Includes temperature, precipitation, and drought index data
- Also, a subset of the Comprehensive Ocean-Atmosphere Dataset is now available
  - a marine database with elements such as sea surface temperature, wave height, and wind speed

Updated Dataset
Recent Publications
- Available via www/mosaic
- The Climate Variations Bulletin with climatic reports and information by month for the U.S.
- Technical Reports on events such as the March 1993 superstorm, the Summer 1993 Midwest floods, and the July 1993 Georgia flood
- The NCDC Products and Services Guide

If you wish to order data (off line) or a publication, please contact:
Climate Services Branch
National Climatic Data Center
151 Patton Avenue
Asheville, NC 28801
Email: orders@ncdc.noaa.gov
Phone: 704-271-4800
Fax: 704-271-4876

If you have any technical questions about these on-line data, or if you encounter access difficulty for more than a day or two, please contact:
Neal Lott or Tom Ross
NCDC/RCSG
151 Patton Avenue
Asheville, NC 28801
Email: nlott@ncdc.noaa.gov / tross@ncdc.noaa.gov
Phone: 704-271-4995 / 704-271-4994
Fax: 704-271-4876

AUGUST UPDATE OF FORECAST FOR 1995
ATLANTIC SEASONAL HURRICANE ACTIVITY

From: Chris Landsea <landsea@enso.atmos.colostate.edu>
(4 August, 1995)
intensity. Hurricanes of Category 3 or higher are considered intense or major storms and have maximum sustained winds of 115 miles per hour or greater. Hurricane Erin, at its height, was a Category 1 hurricane. Hurricane Allison was only a weak Category 1 hurricane when it came ashore.

No category 3, 4 or 5 hurricanes occurred in 1994. Hurricanes Hugo and Andrew both were Category 4 storms when they came ashore.

Gray and his research team use five primary factors in their forecast: the strength or weakness of El Nino; the direction of equatorial stratospheric winds at 68,000-75,000 feet and the tropospheric winds at 40,000 feet; rainfall in the West African Sahel region; temperature and pressure readings in West Africa; and Atlantic Ocean and Caribbean Sea-level pressure readings and other factors.

The team’s hurricane forecasts are for hurricanes that form in the Atlantic Basin, the region including the Atlantic Ocean, the Caribbean Sea and the Gulf of Mexico. The research team’s forecasts do not predict landfall.

"We hope many of the storms that do form either will not come ashore or will miss populated areas," Gray said. "However, the more storms there are, especially the intense or major hurricanes, the more likely we are to see storm damage."

Overall, today’s forecast calls for a season with a Net Tropical Cyclone Activity level of 130 percent of normal, compared to average activity over the last 45 years. That’s down slightly from the 140 percent Net Tropical Cyclone Activity the team forecast in June. Net Tropical Cyclone Activity is a measure of all tropical storm, hurricane and intense hurricane activity. The forecast also predicts a Hurricane Destruction Potential rating of 90 for the 1995 season. The typical year has a rating of 68, while the average over the last four years has been 41.

The latest forecast also calls for 30 hurricane days, or four, six-hour periods when hurricanes attain winds of 74 miles per hour or greater. The forecast also predicts 65 tropical storm days, or the same time period in which tropical storms attain winds of 39 miles per hour or greater.

The forecasts are issued in June, August and November. The research team members are the only scientists who annually issue long-range seasonal hurricane forecasts.

"By working as a team, we can do a pretty good job of predicting what will occur with some skill," Gray said.

**Forecasts of 1995 Hurricane Activity.**

<table>
<thead>
<tr>
<th></th>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>named storms (N=9.3)</td>
<td>16</td>
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<tr>
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<td>8</td>
<td>8</td>
<td>8</td>
<td>158%</td>
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<tr>
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<td>130%</td>
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<tr>
<td>intense hurricanes (IH=2.1)</td>
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<td>3</td>
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<tr>
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<tr>
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<td>90</td>
<td>110</td>
<td>85</td>
<td>132%</td>
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</tr>
<tr>
<td>potential (HDP=68)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>net tropical cyclone</td>
<td>130</td>
<td>140</td>
<td>140</td>
<td>130%</td>
<td></td>
</tr>
</tbody>
</table>

**1994 Hurricane Activity and Last Year’s Forecasts.**

<table>
<thead>
<tr>
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<tbody>
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<tr>
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<td>1</td>
<td>7</td>
</tr>
<tr>
<td>hurricane destruction</td>
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<td>35</td>
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</tr>
<tr>
<td>potential (HDP=68)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>net tropical cyclone</td>
<td>37</td>
<td>55</td>
<td>70</td>
<td>110</td>
</tr>
</tbody>
</table>

( ) represents the number in this category that occur in a typical year.

# Hurricane Destruction Potential measures a hurricane’s potential for wind- and ocean-surge damage.

**SOURCES FOR OZONE INFORMATION ON WWW**

16 September 1995

New bulletins on the current state of stratospheric ozone over the Antarctic from the British Antarctic Survey and the World Meteorological Organization are available on the SOLIS...
(Stratospheric Ozone Law, Information and Science) Web site.

The latest editions are: BAS Ozone Bulletin 04/95 of 15 September 1995, and WMO Ozone Bulletin 03/95 of 14 September. They are accessible from the SOLIS science page, at:

< URL:http://www.acd.ucar.edu/gpdf/ozone/science/>

New bulletins are issued in both series at approximately 10-14 day intervals.

Gregory P. Dubois-Felsmann
< gpdf@acd.ucar.edu>
National Center for Atmospheric Research

**EOSDIS V0/IMS ONLINE**

**Overview of EOSDIS and DAACs**

The NASA EOS Data and Information System (EOSDIS) provides users with existing Earth Science data and in the future management and access will be provided to data products from Earth Observing System (EOS) satellite instruments. Within EOSDIS, the Distributed Active Archive Centers (DAACs) are responsible for providing data and information services to support the global change research community.

Each of the nine DAACs now has significant data holdings. A subset of the holdings can be searched based on geophysical parameters and ordered via the Version 0 Information Management System (V0 IMS) prototype. Data can also be ordered via e-mail, fax, phone, mail, and in some cases through the World Wide Web and heritage order systems which pre-date EOSDIS.

In addition to the EOSDIS DAACs, there are a number of different agencies and data centers cooperating to make data more accessible.

One example of this is the Satellite Active Archive (SAA) developed by the National Oceanic and Atmospheric Administration (NOAA) which is searchable using the V0 IMS prototype.

**The role of the V0 IMS prototype**

The V0 IMS prototype, (released in August 1994), is seen as an important step towards the realization of interdisciplinary Earth science research. Historically it has been difficult for scientists conducting interdisciplinary research to locate data. The V0 IMS overcomes that difficulty by allowing a user to search for and order data from any DAAC, or combination of DAACs, in a single on-line session. The search can be based on a number of criteria that include time, space, geophysical parameter, sensor and instrument. The V0 IMS prototype is linked to the GCMD such that the DIFs (Directory Interchange Formats which describe a product) are accessible. In addition, online documents known as Guides provide comprehensive information about the data products.

There has been a strong emphasis on providing data in a common format so that data from different sources can be readily compared. EOSDIS has selected HDF (Hierarchical Data Format), a format that has been developed by the National Center for Supercomputing Applications) NCSA. NCSA has also developed S/W software to work with HDF. Development of both HDF and associated software is on-going.

**Accessing the V0 IMS prototype**

The Version 0 IMS prototype offers both a Graphical User Interface (GUI) and a Character User Interface (ChUI). Running the GUI requires a workstation, X terminal, or PC/Macintosh capable of running the X Windows System (or an X terminal emulator such as MacX), with a 1024x768 pixel color display. System response time for the Version 0 IMS Graphical User Interface (GUI) will be limited by the capacity of the network connection between the user site and the DAAC the user accesses. Generally, a communications capacity of 56kths is needed for good performance. The ChUI requires less communications bandwidth and thus performs better where network capacity is limited. Running the ChUI requires a PC/Macintosh using a VT100 emulator or any VT100 compatible terminal.

Users may access the Version 0 IMS prototype from the WWW Version 0 IMS Home Page by selecting Access to the EOSDIS V0 IMS. (URL: http://harp.gsfc.nasa.gov:1729/eosdis_documents/). Links are also provided by the individual DAACs.

A Web version of the IMS has recently developed and is expected to be available in fall 1995.

**V0 IMS prototype evaluation**

As would be expected with a prototype, there are some rough edges, both in terms of minor problems with the system and with performance. Comments on this system are welcome.
Archives and Discipline areas

The DAACs and the SAA are listed below with their subject areas, contact information and VO IMS telnet access.

**ASF DAAC - SAR Products & Polar Processes**  
Voice: 907-474-6166  Fax: 907-474-5195  
Internet: asf@eos.nasa.gov  
WWW URL: http://eosims.asf.alaska.edu:12355/  
V0 IMS prototype telnet access: eosims.asf.alaska.edu:12345

**EDC DAAC - Land Processes**  
Voice: 605-594-6116  Fax: 605-594-6589  
Internet: edc@eos.nasa.gov  
WWW URL: http://sunl.cr.usgs.gov/landdaac/landdaac.html  
V0 IMS prototype telnet access: eosims.cr.usgs.gov:12345

**GSFC DAAC - Upper Atmosphere, Global Biosphere**  
Voice: 301-286-3209  Fax: 301-286-1775  
Internet: gsfc@eos.nasa.gov  
WWW URL: http://daac.gsfc.nasa.gov  
V0 IMS prototype telnet access: eosims.gsfc.nasa.gov:12345

**JPL DAAC - Physical Oceanography**  
Voice : 818-354-9890  Fax: 818-393-2718  
Internet: jpl@eos.nasa.gov  
V0 IMS prototype telnet access: eosims.jpl.nasa.gov:12345

**LaRC DAAC - Radiation Budget, Tropospheric Chemistry**  
Voice: 804-864-8566  Fax: 804-864-8807  
Internet: larc@eos.nasa.gov  
WWW URL: http://eosdis.larc.nasa.gov  
V0 IMS prototype telnet access: eosims.larc.nasa.gov:12345

**MSFC DAAC - Hydrologic Cycle**  
Voice: 205-922-5932  Fax: 205-922-5859  
Internet: msfc@eos.nasa.gov  
WWW URL: http://www.daac.msfc.nasa.gov/  
V0 IMS prototype telnet access: eosims.msfc.nasa.gov:12345

**NSIDC DAAC - Snow and Ice, Cryosphere and Climate**  
Voice: 303-492-6199  Fax: 303-492-2468  
Internet: nsidc@eos.nasa.gov  
WWW URL: http://eosims.colorado.edu:1733  
V0 IMS prototype telnet access: eosims.colorado.edu:12345

**ORNL DAAC - Biogeochemical Dynamics**  
Voice: 615-241-3952  Fax: 615-574-4665  
Internet: ornl@eos.nasa.gov  
WWW URL: http://www-eosdis.oml.gov/  
V0 IMS prototype telnet access: eosims.esd.oml.gov:12345

**SEDAC - Human Impact on Global Change**  
Voice: 517-797-2727  Fax: 517-797-2622  
Internet: sedac@eos.nasa.gov  
WWW URL: http://www.ciesin.org  
V0 IMS prototype telnet access: eosims.esd.orl.gov:12345

**NOAA SAA - Satellite Earth Sciences Data**  
Voice: 301 763-8400  Fax: 301 763-8443  
Internet: sdsdreq@ncdc.noaa.gov  
WWW URL: http://ns.noaa.gov/saa/homepage.html  
V0 IMS prototype telnet access: eosims.saa.noaa.gov:12345

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**ANNOUNCING THE CESNA HOMEPAGE**

17 October, 1995

The Climatic Expert System for the North Atlantic (CESNA) has been under development at the University of Colorado since 1994. CESNA is designed to make predictions for mean seasonal climatic characteristics one year in advance. The current version of the system can make predictions for eastern North America, the North Atlantic and adjacent Arctic Seas and parts of Europe. Forecasts for 1996, along with a description of the system, are now available on the Internet. We invite you to visit the CESNA homepage at:

http://www.cs.colorado.edu/~sergei/cesna.html

Questions, comments and suggestions are welcome.

Sergei Rodionov  
Computer Science Department  
Engineering Center, ECOT 7-15  
Campus Box 430  
University of Colorado  
Boulder, CO 80309-0430, USA  
tel.: +1 303 673 9598  fax: +1 303 492 2844  
e-mail: sergei@cs.colorado.edu  
http://www.cs.colorado.edu/~sergei/Home.html

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**ANNOUNCING NEW EOSDIS LANGLEY RESEARCH DAAC HOMEPAGE**

25 October 1995
The Earth Observing System Data Information System (EOSDIS) Langley Research Center Distributed Active Archive Center (DAAC) announces the release of its new home page. The new features of the Langley DAAC Homepage include:

* A Web order form for prepackaged CD-ROMs and video tapes
* Data sets and images that can be downloaded directly from the Web
* Online html version of the Langley DAAC Handbook
* A Character User Interface (ChUI) ordering system tutorial
* An expanded Graphical User Interface (GUI) tutorial
* Easy access to documentation and data set information

The url for the Langley DAAC homepage is http://eosdis.larc.nasa.gov/

Please access our home page and let us know what you think of it.

**TYPES OF DATA:**

The Langley Distributed Active Archive Center, located in Hampton, Virginia, is responsible for the archival and distribution of NASA science data in the areas of radiation budget, clouds, aerosols and tropospheric chemistry. The Langley DAAC will also archive some of the data sets which result from the EOS program and other elements of Mission to Planet Earth. Currently archived and available for distribution is data from the Earth's Radiation Budget Experiment (ERBE), the International Satellite Cloud Climatology Project (ISCCP), the Stratospheric Aerosol and Gas Experiment (SAGE), the Surface Radiation Budget (SRB), the First ISCCP Regional Experiment (FIRE), the Global Tropospheric Experiment (GTE) and the Stratospheric Aerosol Measurement (SAM) II.

**FREE GLOBAL DATA AVAILABLE FROM THE NASA/GSFC DAAC**

31 October 1995

The Distributed Active Archive Center (DAAC) at Goddard Space Flight Center gives away data for studying and learning about atmospheric dynamics, the upper atmosphere, and Earth's vegetation. You can use these data to study:

* greenhouse global warming
* deforestation and desertification and their role in climate change
* ozone depletion
* El Nino effect on weather and climate
* impact of volcano eruptions on ozone concentration
* the role of ocean in global climate

and more. All Goddard DAAC products are FREE and available ON LINE.

Our Help Desk will answer your questions!

**address:** GSFC DAAC User Services NASA/Goddard Space Flight Center Code 902.2 Greenbelt, MD 20771

email: daacuso@daac.gsfc.nasa.gov

voice: 301-286-3209 (9-5 ET, Mon-Fri)

fax: 301-286-0268

URL: http://daac.gsfc.nasa.gov/

You can order any product listed below by putting an X between the brackets ([x]) and e-mailing portion back to us.

[ ] An Overview of Goddard DAAC Products and Services
What is the Goddard DAAC?
What's in the Goddard DAAC collection?
How do I obtain data?
What else comes with the data?
What about other types of data?

[ ] "The Goddard DAAC. A Source for Global Earth Science Data"
A brochure--all the info in the overview and then some.

[ ] Sample Images of Goddard DAAC Data Sets
Hardcopy color slides, color transparencies

[ ] Introductory Information for Each Goddard DAAC Data Set
(from their README files)

[ ] Ozone, Ice, Clouds, TRMM images from PAO.

[ ] The GEDEX CD-ROM Set
The Greenhouse Effect Detection Experiment (GEDEX) data collection contains over 60 data sets with parameters relevant to greenhouse gas effect research (surface and upper air temperature, solar irradiiances, radiation...
budget, clouds, and greenhouse gases). Many data sets are available for a 10 year period spanning the 1980s. Depending on the data set, coverage is global, regional, or local.

[] ISLSCP CD-ROM Set
The International Satellite Land Surface Climatology Project Initiative I - Global Data Sets for Land-Atmosphere Models, data collection contains vegetation and biophysics, hydrology, near surface meteorology, radiation, soils, snow, and ice parameters. Monthly, monthly-6 hourly, and some 6-hourly data are available globally for 1987 through 1988 on a common 1-degree grid.

[] TOMS CD-ROM Set
The Nimbus-7 Total Ozone Mapping Spectrometer (TOMS) Level 3 data contain global, daily, total-ozone values at 1.25-degree spatial resolution. Data are divided into gridded values, global images, overpass, and SBUV solar flux ozone data from November 1978 to April 1992 on three CDs.

[] PAL CD-ROM Set
The Pathfinder Advanced Very High Resolution Radiometer (AVHRR) Land (PAL) Level 3 data, contains 1986, subsetted, 8 km resolution, global 10-day composites. Data include Normalized Difference Vegetation Index, Channel-1 and -2 reflectances, and Channel-4 and -5 brightness temperatures. This product not intended for research use.

[] EOS (Earth Observing Satellite) Brochure from the EOS Science Office
Includes a booklet describing the EOS project, purpose, and services; images from various satellite platforms; descriptions of planned launches of EOS satellite platforms; a listing of relevant EOS-related acronyms; and an EOS sticker

[] EOS Poster Set
Contains images and information on a range of topics including
  * cloud radiative effects
  * global ice and sea level changes
  * vegetation and hydrology changes
  * ozone depletion
  * impact of volcanos
  * greenhouse effect
  * ocean processes

[] Most Recent Copy of the EOS bimonthly newsletter, "The Earth Observer"

[] Most Recent Copy of the Goddard DAAC Periodic Newsletter, "Data Streams"

[] NASA Fact Sheets from the Science Office
Information covers
  * volcanos and global climate change
  * El Nino
  * clouds and the energy cycle
  * global warming
  * polar ice
  * biosphere
  * ozone

Mark your choices, include your complete mailing address with a daytime phone number and send this back to daacust@daac.gsfc.nasa.gov.

The Goddard DAAC Mission
The Goddard DAAC's mission is to maximize the investment benefit of the Mission to Planet Earth by providing data and services that help people fully realize the scientific and educational potential of global climate data.

NCDC (USA) - LATEST TECH REPORT
24 November 1995
The National Climatic Data Center (NCDC) announces the release of its latest Research Customer Service Group Technical Report TR 95-02, "Hurricane Opal."

The report includes:
  - Narrative about the storm and its impact
  - Tables showing the storm's track, rainfall amounts, and peak wind gusts
  - Several maps showing the rainfall and wind data
  - Satellite images—visible, infrared (color), and water vapor
  - NEXRAD radar images (color)

The report will be placed on line via our homepage (http://www.ncdc.noaa.gov) in the near future, and is currently available free of charge from NCDC.
BIOGEOCHEMICAL AND ECOLOGICAL DATA AVAILABLE ON WWW

24 November 1995

The Oak Ridge National Laboratory Distributed Archive Archive Center announces an updated Web site. With this new version, users can access:

- BIOME, our Web-based data search-and-order system;
- field campaign data - FIFE and OTTER;
- global NPP data;
- CDIAC data;
- new data being added continuously; and
- links to improved X-Windows interfaces.

The URL for this Web site is:

http://www-eosdis.ornl.gov

The Oak Ridge National Laboratory (ORNL) Distributed Active Archive Center (DAAC) is one of nine DAACs sponsored by NASA as part of the Earth Observing System Data and Information System (EOSDIS). We focus on biogeochemical dynamics and ecological data based on field measurements with world-wide coverage and on providing data to the global change research community, decision makers, educators, and others.

We encourage you to access our WWW site and to send us suggestions on how we may best meet your data needs.

For further information and assistance, contact:

Jerry Curry or Merilyn Gentry
ORNL DAAC User Services Office
Oak Ridge National Laboratory
P.O. Box 2008, MS 6407
Oak Ridge,
Tennessee 37831-6407
USA

Telephone: (423) 241-3952
FAX: (423) 574-4665
E-mail: ornladc@ornl.gov

SUMMARY OF 1995 ATLANTIC TROPICAL CYCLONE ACTIVITY AND VERIFICATION OF THE AUTHORS' SEASONAL PREDICTION

(A year of unusually high hurricane activity due to the combined effects of very low values of West Atlantic surface pressure, a westerly QBO, a return to cool ENSO conditions and very favorable Atlantic basin tropospheric wind shear conditions)

by

William M. Gray*
Christopher W. Landsea**
Paul W. Mielke, Jr.***
and Kenneth J. Berry****

Department of Atmospheric Sciences
Colorado State University
Fort Collins, CO 80523

(30 November 1995)

DEFINITIONS AND ABBREVIATIONS

Named Storm (NS) - A hurricane or tropical storm.

Named Storm Day (NSD) - Four consecutive six-hour periods during which a tropical cyclone is observed or estimated to have attained tropical storm or hurricane intensity winds.

Hurricane (H) - A tropical cyclone with sustained low level winds of 74 miles per hour (33 ms⁻¹ or 64 knots) or greater.

Hurricane Day (HD) - Four six-hour periods during which a hurricane has sustained winds of 74 miles per hour (33 ms⁻¹ or 64 knots) or greater.

Hurricane Destruction Potential (HDP) - A measure of a hurricane's potential for wind and storm surge destruction. HDP is defined as the

HKMetS BULLETIN Vol. 5, No. 2, 1995
sum of the square of a hurricane's maximum wind speed during each six-hour period of its existence. This value is summed for the season.

Net Tropical Cyclone Activity (NTC) - A combined measure of the average seasonal percentage of NS, NSD, H, HD, IH, and IHD to their long term mean.

**ABSTRACT**

This paper summarizes the tropical cyclone (TC) activity which occurred in the Atlantic Basin during 1995 and verifies the author's seasonal forecast of this activity which was initially issued on 30 November of last year, with updates on 5 June and 4 August of this year. The 1995 hurricane season was a year of near record hurricane activity. There was a total of 19 named storms (average 9.3) and 11 hurricanes (average 5.7) which persisted for a total of 62 days (average is 23). There were 5 major (intense) hurricanes of Saffir/Simpson category 3-4-5 (average is 2.1 intense hurricanes) with 11.5 intense storm days (average is 4.5). The seasonal total of named storm days was 121 or 262 percent of average and net tropical cyclone (NTC) activity was 237 percent of the average for the last 45 years.

This unusually active hurricane season was the result of the concurrence of nearly all the physical factors known to enhance seasonal hurricane activity. This convergence of favorable factors typically occurs about once every 10-15 years. Of all these favorable factors, low values of surface pressure during 1995 were the most important. Our 1995 seasonal forecasts made on 30 November 1994, 5 June 1995 and 4 August 1995, all called for above average hurricane activity though not nearly as much hurricane activity as occurred.

**SUMMARY OF 1995 ATLANTIC TROPICAL CYCLONE ACTIVITY**

The 1995 Atlantic hurricane season officially ends on 30 November. There were 11 hurricanes (maximum sustained winds > 73 mph) and 62 hurricane days during the 1995 season. The total named storms (or the sum of the number of hurricanes and tropical storms) was 19, yielding 121 named storm days. There were 5 major (intense) hurricanes this season. All designated tropical cyclone activity parameters were much above the long period average values.

Table 1 provides statistical parameters for the 1995 season. Table 2 compares 1995 seasonal tropical cyclone activity as a percentage of the last 45-year climatology. Table 3 shows a comparison of the 1995 hurricane season with the last four seasons 1991-1994. Note the more active 1995 season in comparison with 1991

<table>
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<th>Forecast Parameter</th>
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<th>'94</th>
<th>'93</th>
<th>'92</th>
<th>'91</th>
<th>total for 1991-94</th>
</tr>
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<td>3</td>
<td>4</td>
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</tr>
<tr>
<td>Named storms (NS)</td>
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<td>7</td>
<td>8</td>
<td>6</td>
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<td>29</td>
</tr>
<tr>
<td>Hurricane days (HD)</td>
<td>62</td>
<td>7</td>
<td>10</td>
<td>16</td>
<td>8</td>
<td>41</td>
</tr>
<tr>
<td>Named storm days (NSD)</td>
<td>121</td>
<td>28</td>
<td>30</td>
<td>38</td>
<td>22</td>
<td>118</td>
</tr>
<tr>
<td>Hurricane destruction potential (HDP)</td>
<td>172</td>
<td>23</td>
<td>17</td>
<td>23</td>
<td>112</td>
<td></td>
</tr>
<tr>
<td>Intense hurricanes (IH)</td>
<td>5</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>Intense hurricane days (IHD)</td>
<td>12</td>
<td>0</td>
<td>0.75</td>
<td>3.25</td>
<td>1.25</td>
<td>5.25</td>
</tr>
<tr>
<td>Net tropical cyclone activity (NTC)</td>
<td>237</td>
<td>37</td>
<td>55</td>
<td>62</td>
<td>59</td>
<td>213</td>
</tr>
</tbody>
</table>

through 1994. In fact, in terms of number of hurricane days (HD), intense hurricanes (IH), intense hurricane days (IHD), hurricane destruction potential (HDP) and net tropical cyclone activity (NTC), 1995 values were higher than the total combined amount for these parameters during all of the four previous seasons (1991-1994). Clearly, 1995 represents a remarkable upsurge in hurricane activity.

Comparisons of the 1995 season with other active Atlantic basin seasons vary depending on what seasonal parameters are examined. These may include the number of named storms, number of hurricanes, or number of major category 3-4-5 storms as representative of seasonal activity. However, the number of named storm days, hurricane days, major hurricane days are also important representations of seasonal activity. We advocate use of a parameter termed the "Net Tropical Cyclone" (NTC) activity to characterize how active the season has been. NTC combines all six of the above mentioned measures of tropical cyclone activity (see the Appendix for a more detailed definition of this parameter).

COMPARISON OF 1995 WITH OTHER ACTIVE HURRICANE SEASONS OF THE PAST

Going back 120 years we find 10 other hurricane seasons with hurricane activity comparable to 1995. These very active years occur on average about every 10-15 years and are listed in Table 4. It is on this scale that a large percentage of the global atmospheric conditions associated with active hurricane seasons combine in a favorable mode to produce very active hurricane seasons.

The 1995 active hurricane season is not unprecedented. In terms of total named storms (NS), 1993 had two more than this year (21 total), 1969 two less (17), 1887 two less (17), and 1936 two less (17). In terms of the total number of hurricanes (H), the 1995 value of 11 was exceeded only in 1969 (12), was equalled in 1950 and 1916 (11 each) and there was only one less hurricane in 1933, 1893 and 1887 (10 each). In terms of net tropical cyclone activity (NTC) the value 237 for 1995 was exceeded in 1950 (262), 1933 (273), 1926 (287), 1916 (255), and 1893 (286). NTC was only somewhat less in 1961 (222) and 1958 (198). The 1995 hurricane destruction potential (HDP) value of 172 was exceeded in 1950 (200), 1926 (197) and 1893 (230). The total of 5 intense or major hurricane (IH) activity in 1995 was exceeded in 1950 (7) and 1961, 1926 and 1916 with 6 each. The 1995 named storm days (NSD) value of 121 exceeds all previous years except 1933 (136). Thus, although 1995 was a very active year for hurricanes, a number of other seasons during the last 120 years were as active or nearly as active as this year.

Table 4: Comparison of 1995 hurricane activity with the ten most active hurricane seasons during the last 120 years.

<table>
<thead>
<tr>
<th>Forecast Parameter</th>
<th>'95</th>
<th>'94</th>
<th>'93</th>
<th>'92</th>
<th>'91</th>
<th>total for 1991-94</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hurricanes (H)</td>
<td>11</td>
<td>3</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>15</td>
</tr>
<tr>
<td>Named storms (NS)</td>
<td>19</td>
<td>7</td>
<td>8</td>
<td>6</td>
<td>8</td>
<td>29</td>
</tr>
<tr>
<td>Hurricane days (HD)</td>
<td>62</td>
<td>7</td>
<td>10</td>
<td>16</td>
<td>8</td>
<td>41</td>
</tr>
<tr>
<td>Named storm days (NSD)</td>
<td>121</td>
<td>28</td>
<td>30</td>
<td>38</td>
<td>22</td>
<td>118</td>
</tr>
<tr>
<td>Hurricane destruction potential (HDP)</td>
<td>172</td>
<td>23</td>
<td>17</td>
<td>23</td>
<td>112</td>
<td></td>
</tr>
<tr>
<td>Intense hurricanes (IH)</td>
<td>5</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>Intense hurricane days (IHD)</td>
<td>12</td>
<td>0</td>
<td>0.75</td>
<td>3.25</td>
<td>1.25</td>
<td>5.25</td>
</tr>
<tr>
<td>Net tropical cyclone activity (NTC)</td>
<td>237</td>
<td>37</td>
<td>55</td>
<td>62</td>
<td>59</td>
<td>213</td>
</tr>
</tbody>
</table>

LOW LATITUDE FORMATION AND TRACK RECURRENCE

In contrast with the previous four years (1991-1994) there was a sharp increase in the amount of low latitude hurricane formation events during 1995. Only two hurricanes formed equatorwards of 25°N during the four years 1991-1994. In contrast, no less than nine hurricanes formed equatorward of 25°N during 1995 - an 18 fold increase. Typically, it is hurricanes which form at low latitudes that cause the majority of the hurricane spawned destruction. In this regard, the US was very fortunate during the unusually
active 1995 hurricane season. The location of a persistent mid- and upper-tropospheric trough along the US East Coast imposed mean upper level cyclone steering winds which were more from the south than usual. This circulation feature caused the majority of this season's hurricanes and tropical cyclones to turn more northward and then northeastward into the westerly winds before they had a chance to reach the US mainland. Although hurricanes Allison and Erin made landfall on the US, it was only hurricane Opal which brought major damage and destruction to the US mainland. In other, less fortunate than the US mainland. Intense hurricanes, Luis, Marilyn and Roxanne caused a great deal of destruction, particularly to the US Virgin Islands.

**TIMING OF 1995 SEASONAL ACTIVITY**

Tropical cyclone formation during the very active 1995 hurricane season can be seen to have occurred in two active 30 day periods (28 July - 29 August and 27 September - 27 October) straddling an inactive 30-day period at the very climatological center of the hurricane season when only one named storm (intense hurricane Marilyn; September 12-22) formed.

Tropical cyclone activity in 1995 began early when hurricane Allison formed in the Eastern Gulf of Mexico during early June. Two named storms (Barry and Chantal) formed during the first half of July. But what was most distinctive about the 1995 hurricane season was the nine named storms (Dean, Erin, Felix, Gabrielle, Humberto, Iris, Jerry, Karen and Luis) which formed during the period between 31 July and 27 August. This is equivalent to a new named storm formation about every three days. Of these nine named storms, five became hurricanes (Erin, Felix, Humberto, Iris and Luis) and two became intense category 4 hurricanes (Felix and Luis).

It was during this August period when the West Atlantic environmental conditions became ideal for tropical cyclone formation. Sea level pressure and tropospheric wind shear conditions in the Western Atlantic were both about two standard deviations below August average conditions (see Tables 9 and 10). After 27 August there was a sharp 30-day downturn in new name storm formation. Between August 27, when Luis was named, and September 27 when Noel and Opal were named, only one new system - intense hurricane, Marilyn, formed. Such a sharp 30-day downturn in new formations is typical of active hurricane seasons. It is common to have a clustering of tropical cyclone activity over 20-30 day periods interspersed with similar 20-30 day periods when new tropical cyclone formation becomes much less frequent. It is to be noted that the downturn of hurricane activity during the 1995 season occurred during the climatological height of the hurricane season in September. September is the month usually experiencing the largest numbers of tropical cyclone formations; the peak of the hurricane season being September 10th. The general September downturn in new name storm formation is well associated with changes to less favorable environmental conditions. Higher sea level pressure anomalies and increased Western Tropical Atlantic wind shear conditions developed during much of September 1995.

The second burst of new name storm formation occurred between 27 September and 27 October when six additional new name storms formed. Of these new storms four became hurricanes and two became intense hurricanes (Noel - H, Opal - IH, Pablo - TS, Roxanne - IH, Sebastien - TS and Tanya - H). It was in late September and October when western Atlantic sea level pressure and tropospheric vertical wind shear were again reduced.

**FACTORS KNOWN TO BE ASSOCIATED WITH ATLANTIC SEASONAL HURRICANE ACTIVITY**

Seasonal hurricane forecasts are based on the current values of indices derived from various global and regional scale predictive factors which the authors have previously shown to be statistically related to seasonal variations of hurricane activity. Successive sets of values of these predictive factors are obtained, first during late November of the previous year and then updated during early June of the concurrent year (the official start of the hurricane season) and during early August (just before the start of the active portion of the hurricane season). These predictive factors include the following:

(a) The stratospheric Quasi-Biennial Oscillation (QBO) influence. The QBO refers to variable east-west oscillating stratospheric winds which circle the globe near the equator. On average, there is nearly twice as much intense (category 3-4-5) Atlantic basin hurricane activity during seasons when the equatorial stratospheric winds at 30 hPa and 50 hPa (23 and 20 km altitude, respectively) are more westerly as compared to when they are from a more easterly direction.
During the 1995 season, these QBO winds were from a relative westerly direction. This was an enhancing influence for this season’s hurricane activity.

(b) El Nino-Southern Oscillation (ENSO) influence: ENSO characterizes the sea surface temperature anomalies in the eastern equatorial Pacific and the value of Tahiti minus Darwin surface pressure gradient. The effects of a moderate or strong El Nino (warm Nino-3 water and low values of Tahiti minus Darwin sea level pressure difference) event in the eastern equatorial Pacific are to reduce Atlantic basin hurricane activity. By contrast, in those seasons with cold Nino-3 sea surface temperatures and high values of Tahiti minus Darwin surface pressure occur (La Nina years), there is typically an enhancement of Atlantic basin hurricane activity. These differences are related to alterations of upper tropospheric (200 hPa or 12 km) westerly winds and surface pressure over the Caribbean Basin and western Atlantic. Westerly winds are enhanced during El Nino seasons and this condition creates strong vertical wind shear over the Atlantic, inhibiting hurricane activity. During La Nina (or cold) years, westerly upper-tropospheric winds and the associated vertical wind shear are reduced and hurricane activity is typically greater. The unusually persistent 1991-94 El Nino-like conditions finally ran their course and neutral to cold water conditions settled into the equatorial Pacific during August and September of this year, thereby becoming an enhancing influence on this year’s Atlantic basin hurricane activity.

(c) African Rainfall (AR) influence: The incidence of intense Atlantic hurricane activity is strongly enhanced during those seasons when rainfall during June-July in the Western Sahel is above average and when August-November rainfall in Gulf of Guinea region during the prior year is above average. Hurricane activity is typically suppressed if the rainfall in these two regions was below average. Rainfall amounts for both the Western Sahel and the Gulf of Guinea were near average for 1995. This did not cause a suppression of this year’s hurricane activity as has occurred in most of the last 25 hurricane seasons.

(d) Influence of West Africa west-to-east surface pressure and temperature gradients (delta PT): We find that Atlantic hurricane activity is enhanced when the February to May east minus west pressure gradient in West Africa is higher than normal and/or when the east minus west temperature gradient anomaly is below average.

These February through May 1995 pressure and temperature gradients indicated a forthcoming average North African monsoon with a near average amount of seasonal hurricane activity - not the distinctly below average conditions as occurred during most of the last quarter century.

(e) Caribbean Basin Sea Level Pressure Anomaly (SLPA) and upper tropospheric (12 km) Zonal Wind Anomaly (ZWA) influence. SLPA and ZWA have a strong association with Atlantic Basin hurricane activity. Values of SLPA and ZWA for 1995 were both below average, indicating an enhancing influence on this season’s hurricane activity.

WHY 1995 WAS SUCH AN ACTIVE HURRICANE SEASON

Nearly all of the climate forecast parameters which we use to forecast Atlantic Basin hurricane activity took on positive (for hurricane activity) values during 1995, thereby contributing to the unusually active hurricane season. These are listed in Table 5. The favorable factors for hurricane enhancing climate were:

1. The westerly stratospheric QBO
3. Lack of drought in the Western Sahel region.
4. Much below average sea-level pressure in the Caribbean Basin.
5. Eastern 200 hPa zonal wind anomalies over the tropical Atlantic.

Table 5: Listing and specific values for 1995 environmental conditions during August and September 1995 which contributed to very high hurricane activity.

<table>
<thead>
<tr>
<th>Environmental Condition</th>
<th>1995 Specific Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. QBO Relative Winds at 10-15°N</td>
<td>30 hPa + 10 ms⁻¹</td>
</tr>
<tr>
<td></td>
<td>50 hPa + 11 ms⁻¹</td>
</tr>
<tr>
<td>2. Nino-3 SST</td>
<td>-0.57 °C</td>
</tr>
<tr>
<td>3. June-Sept Western Sahel Rainfall</td>
<td>- 0.48 S.D.</td>
</tr>
<tr>
<td>4. Caribbean Basin Sea-level Pressure Anomaly (SLPA)</td>
<td>- 1.5 hPa</td>
</tr>
<tr>
<td>5. Caribbean Basin 200 hPa Zonal Wind Anomaly (ZWA)</td>
<td>+ 4.0 ms⁻¹</td>
</tr>
</tbody>
</table>

OTHER PREDICTIVE FACTORS WHICH INDICATED AN ACTIVE HURRICANE SEASON FOR 1995

Besides these major climate factors there were...
Table 6: Sea surface temperature anomalies (SSTA) °C in the equatorial Pacific of NINO-3 during the years of 1990-1995 and anticipated SSTA conditions through November 1996. Note cooling has been present since April 1995.

<table>
<thead>
<tr>
<th>Year</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
</tr>
</thead>
<tbody>
<tr>
<td>1990</td>
<td>0.4</td>
<td>0.3</td>
<td>0.5</td>
<td>0.6</td>
<td>0.3</td>
<td>0.0</td>
<td>0.1</td>
<td>0.2</td>
<td>0.2</td>
<td>0.0</td>
<td>0.2</td>
<td>0.4</td>
</tr>
<tr>
<td>1991</td>
<td>0.4</td>
<td>0.2</td>
<td>0.3</td>
<td>0.4</td>
<td>1.0</td>
<td>1.3</td>
<td>1.0</td>
<td>0.5</td>
<td>0.6</td>
<td>0.8</td>
<td>1.1</td>
<td>1.2</td>
</tr>
<tr>
<td>1992</td>
<td>1.5</td>
<td>1.4</td>
<td>1.3</td>
<td>1.4</td>
<td>1.6</td>
<td>0.7</td>
<td>0.1</td>
<td>-0.2</td>
<td>0.1</td>
<td>-0.1</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>1993</td>
<td>0.1</td>
<td>0.3</td>
<td>0.8</td>
<td>1.2</td>
<td>1.7</td>
<td>0.8</td>
<td>0.3</td>
<td>0.0</td>
<td>0.3</td>
<td>0.4</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>1994</td>
<td>0.4</td>
<td>0.0</td>
<td>0.1</td>
<td>0.2</td>
<td>0.4</td>
<td>0.4</td>
<td>-0.2</td>
<td>-0.1</td>
<td>0.2</td>
<td>0.7</td>
<td>1.1</td>
<td>1.2</td>
</tr>
<tr>
<td>1995</td>
<td>1.0</td>
<td>0.7</td>
<td>0.2</td>
<td>-0.2</td>
<td>-0.4</td>
<td>-0.1</td>
<td>0.0</td>
<td>-0.5</td>
<td>-0.6</td>
<td>(-0.7)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1996</td>
<td>Expected to continue on the cool side est.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Other factors not explicitly included in our forecast which also indicated that an active hurricane season was in store for 1995. This included:

1. The usually warm SSTA conditions off of the Northwestern African coastline which extended far westward to near Bermuda.
2. Lower Atlantic sub-tropical pressure anomaly and weaker than normal Atlantic tradewind conditions.
3. A stronger than normal 200 hPa tropical easterly jet extending westward across the Atlantic from Africa.
4. Stronger than normal tropical wave activity coming out of West Africa.
5. Higher surface layer salinity contents in the far North Atlantic, indicating a possible speed-up of the Atlantic Ocean thermohaline circulation.
6. High amount of India, Indonesia, and general Asian monsoon rainfall indicating that a return to cooler ENSO conditions was likely in progress.
7. Lower than normal Singapore 100 hPa temperature anomalies during the summer and fall of 1994.

These additional factors added support for further justification as to why 1995 was such an active hurricane season.

DETAILS AND SPECIFIC VALUES FOR THE 1995 SEASONAL HURRICANE PREDICTORS

a) ENSO

An El Nino like warm water event began forming in the tropical Pacific in late 1989 and El Nino-like conditions persisted in a complicated and somewhat variable mode until the spring of 1995 at which time, an ongoing cooling finally began to emerge. Table 6 provides a tabular summary of Nino-3 sea surface temperature anomaly (SSTA) conditions for the last six years. It is unusual to have El Nino-like conditions persist through five consecutive summers. These warm ENSO conditions, as shown in Table 6, have finally dissipated.

b) Stratospheric QBO Winds

Tables 7 and 8 show both the absolute and relative (i.e., anomaly) values for 30 hPa (23 km) and 50 hPa (20 km) stratospheric QBO zonal winds near 12°N during March through October 1995.

Table 7: Observed March through October 1995 absolute values of stratospheric QBO zonal winds (U) in the (critical) latitude belts between 11-13°N, as obtained from Caribbean stations at Curacao (12°N), Barbados (13°N), and Trinidad (11°N). Values are in ms⁻¹ (as supplied by James Angell and Colin McAdie).

<table>
<thead>
<tr>
<th>Level</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
</tr>
</thead>
<tbody>
<tr>
<td>30 hPa (23 km)</td>
<td>+6</td>
<td>+5</td>
<td>0</td>
<td>-6</td>
<td>-7</td>
<td>-5</td>
<td>-6</td>
<td>-7</td>
</tr>
<tr>
<td>50 hPa (20 km)</td>
<td>+4</td>
<td>+4</td>
<td>+2</td>
<td>-3</td>
<td>-5</td>
<td>-3</td>
<td>+2</td>
<td>+4</td>
</tr>
</tbody>
</table>

Table 8: As in Table 7, but for "relative" or anomalous zonal wind values wherein the annual wind cycle has been removed. Values are in ms⁻¹.

<table>
<thead>
<tr>
<th>Level</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
</tr>
</thead>
<tbody>
<tr>
<td>30 hPa (23 km)</td>
<td>+10</td>
<td>+13</td>
<td>+14</td>
<td>+11</td>
<td>+14</td>
<td>+13</td>
<td>+10</td>
<td>+6</td>
</tr>
<tr>
<td>50 hPa (20 km)</td>
<td>+3</td>
<td>+5</td>
<td>+8</td>
<td>+10</td>
<td>+11</td>
<td>+10</td>
<td>+12</td>
<td>+11</td>
</tr>
</tbody>
</table>
During all of the 1995 hurricane season, QBO winds were from the relatively westerly direction. These QBO wind conditions were an enhancing influence on this year's hurricane activity.

c) Sea-Level Pressure Anomaly (SLPA)

Table 9 gives information on regional Caribbean basin and Gulf of Mexico SLPA during the 1995 season. Note that all stations had quite low SLPA during the months of August through October. During the crucial August-September 1995 period, observed surface pressure values were close to the lowest values observed during the last 45 years. These unusually low August-September surface pressure anomalies for all hurricane months are very consistent with the large amount of tropical cyclone activity which occurred this year.

Table 9: Lower Caribbean basin SLPA for 1995 in hPa (for San Juan, Barbados, Trinidad, Curacao and Cayenne) - top row and for the Caribbean-Gulf of Mexico. Brownsville, Miami, Merida (Mexico), San Juan, Curacao and Barbados - bottom row (as kindly supplied by Colin McAdie of NRC in combination with our CSU analysis).

<table>
<thead>
<tr>
<th></th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
</tr>
</thead>
<tbody>
<tr>
<td>5-Station Lower Caribbean</td>
<td>-0.9</td>
<td>-0.5</td>
<td>0.2</td>
<td>-1.2</td>
<td>-1.3</td>
<td>+0.3</td>
</tr>
<tr>
<td>Average SLPA</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6-Station Caribbean + Gulf</td>
<td>-1.4</td>
<td>-0.4</td>
<td>0.8</td>
<td>-1.2</td>
<td>-2.9</td>
<td>-0.3</td>
</tr>
<tr>
<td>Average SLPA</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Of all the parameters which modify Atlantic seasonal hurricane activity, variations of Caribbean SLPA is one of the strongest. Only tropospheric vertical wind shear is more important. Observations show that summertime Caribbean basin variations in SLPA are independent of ENSO and the QBO. Although SLPA is typically inversely related to western Sahel rainfall, this relationship explains only a small portion of the SLPA variations. We are presently attempting to develop independent methods for making separate predictions of SLPA at both the extended and short range lead times. There appears to be methods for predicting seasonal Caribbean basin SLPA with skill from precursor pressure anomalies in other parts of the globe.

The reduction of hurricane activity due to high pressure in the tropical Atlantic appears to occur in two ways. High Caribbean pressure indicates an equatorward (i.e., southward) shift of the Intertropical Convergence Zone (ITCZ). This condition in turn causes greater subsidence in those Western Atlantic areas into which easterly waves move. Higher pressure also is associated with stronger upper tropospheric zonal winds which act to adversely shear potentially developing systems. It is noted that movement of cloud clusters and easterly waves to a more southerly latitude is less favorable for hurricane formation.

High pressure is also indicative of enhanced Caribbean basin and West Atlantic subsidence and drying. Higher pressure drives stronger low-level divergence and subsidence. This lowers the height of the moist layer and sharpens the trade-wind inversion. Such subsidence makes it more difficult for easterly waves to intensify into named storms. This year subsidence in the western Atlantic was weaker than normal. The upper Caribbean basin and Florida experienced very heavy rain conditions during the summer of 1995, in large measure because of the low-pressure anomaly conditions.

High surface pressure is related to greater rates of tropospheric subsidence and low-level divergence. Such large rates of subsidence lead to enhanced tropospheric drying and humidity decrease. A stronger ~ 2-3 km high tradewind inversion also develops during high pressure periods. These responses to higher pressure conditions make the development of pre-cyclone weather systems and/or the intensification of already developed systems more difficult. Stronger synoptic forcing influences such as easterly wave induced upward vertical motion is required to overcome these more adverse higher subsidence and higher pressure influences. When surface pressure is lower, the opposite influences are present and cyclone development and cyclone enhancement can occur with less synoptic scale and easterly wave vertical motion forcing.

d) Zonal Wind Anomalies (ZWA)

Table 10 shows that the upper tropospheric Zonal Wind Anomalies (ZWA) were very negative and hence comparatively favorable for 1995 seasonal hurricane activity.

e) African Western Sahel Rainfall in 1995

African Western Sahel rainfall is a very powerful modulator of Atlantic hurricane activity, particularly for intense category 3-4-5 hurricane activity. This direct relationship between Western Sahel rainfall and intense hurricane activity is one of the most powerful of the climate relationships. Typically, when many
category 3-4-5 hurricanes form (as in 1995) the Western Sahel would be expected to be wet. This was not the case this year. Overall, the African Sahel had slightly below average rainfall in the Western Sahel.

Table 10: 1995 Caribbean basin 200 hPa (12 km) Zonal Wind Anomaly (ZWA) in ms\(^{-1}\) (as supplied by Colin McAide of NHC and in combination with CSU data) for the four stations of Kingston (18°N), Curacao (12°N), Barbados (13.5°N), and Trinidad (11°N).

<table>
<thead>
<tr>
<th></th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average ZWA</td>
<td>-2.5</td>
<td>-0.5</td>
<td>-1.6</td>
<td>-4.3</td>
<td>-7.0</td>
<td>-4.1</td>
<td>-0.8</td>
</tr>
</tbody>
</table>

UNITY OF FORECAST PARAMETERS FOR TROPOSPHERIC VERTICAL WIND SHEAR

The most fundamental requirement for active hurricane seasons is that there be little change (shearing) of wind direction and speed between the 1 km (3000 ft) and 12 km (40,000 ft) levels. Most of the global and regional factors (just discussed) associated with either active or inactive Atlantic basin hurricane seasons can be related directly or indirectly to physical processes which govern deep western tropical Atlantic vertical wind shear. For example,

1. Cold or La Nina surface ocean temperature conditions in the equatorial east Pacific are associated with small values of western tropical Atlantic vertical wind shear.

2. Above average rainfall in West Africa is associated with weaker Western Atlantic 1-12 km wind shear and below average rainfall conditions with higher values of tropospheric wind shear.

3. Lower than normal West Atlantic surface pressure is also well related to weaker values of vertical wind shear, higher than normal pressure to larger vertical wind shear.

4. Warm values of sea surface temperature off the west coast off Africa are well related to weaker tradewinds and indirectly to weaker values of tropospheric vertical wind shear and with cold SST conditions, the opposite occurs.

5. Other global circulation parameters including the Singapore 100 hPa (16 km altitude) Temperature Anomaly (TA), the stratospheric Quasi-biennial Oscillation (QBO) wind changes, Calcutta, India surface pressure anomaly, Western African east-west surface temperature and pressure gradients during February through May (and other parameters variations) have less direct but nevertheless meaningful associations with tropical western Atlantic 1 to 12 km vertical wind shear.

During 1995, nearly all of the above factors which influence West Atlantic tropospheric vertical wind shear were in place so as to bring about favorable reduction of vertical wind shear conditions allowing frequent western Atlantic tropical cyclone formation. Some of these favorable environmental associations were not included in our 1995 forecast equations and this may be the main reason that our forecast equations fell short of specifying the full extent of this season's extremely active hurricane season.

CONTRAST OF 1994 AND 1995 HURRICANE SEASONS

There could not be two hurricane seasons more different than 1994 and 1995. During 1994 there were no hurricanes at all for 77 consecutive days during the height of the hurricane season. And, two of the three hurricanes that did form in 1994 did so during November, a month with typically little or no activity. No hurricanes formed during November 1995. The contrast of environmental conditions during these two seasons offers a good explanation as to why these two seasons were so different. Table 11 shows the contrasts

<p>| |</p>
<table>
<thead>
<tr>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) Differences in ZWA</td>
</tr>
</tbody>
</table>

Table 11:

a. Lower Caribbean Zonal Wind Anomalies (ZWA)

<table>
<thead>
<tr>
<th></th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
</tr>
</thead>
<tbody>
<tr>
<td>1994</td>
<td>+1.2</td>
<td>+1.3</td>
<td>+1.0</td>
<td>-1.0</td>
<td>-1.2</td>
<td>+3.8</td>
<td>+0.6</td>
</tr>
<tr>
<td>1995</td>
<td>-2.5</td>
<td>-0.5</td>
<td>-4.3</td>
<td>-7.0</td>
<td>-4.1</td>
<td>-0.8</td>
<td></td>
</tr>
<tr>
<td>Differences</td>
<td>+3.7</td>
<td>+1.8</td>
<td>+2.6</td>
<td>+3.3</td>
<td>+5.8</td>
<td>+7.9</td>
<td>+1.4</td>
</tr>
<tr>
<td>(1994 Minus 1995)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

b. SLPA (6-station - Brownsville, Miami, Merida, San Juan, Barbados, Curacao)

<table>
<thead>
<tr>
<th></th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
</tr>
</thead>
<tbody>
<tr>
<td>1994</td>
<td>+0.7</td>
<td>+0.4</td>
<td>+1.0</td>
<td>+1.0</td>
<td>+1.0</td>
<td>+1.5</td>
<td>-0.3</td>
</tr>
<tr>
<td>1995</td>
<td>-1.4</td>
<td>-0.4</td>
<td>-0.8</td>
<td>-1.2</td>
<td>-2.9</td>
<td>-0.3</td>
<td>-1.4</td>
</tr>
<tr>
<td>Differences</td>
<td>+2.1</td>
<td>+1.0</td>
<td>+1.8</td>
<td>+2.2</td>
<td>+3.9</td>
<td>+1.8</td>
<td>+0.9</td>
</tr>
<tr>
<td>(1994 Minus 1995)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
in western Atlantic surface pressure and 200 hPa (\textasciitilde 40,000 ft) zonal wind differences between these two seasons. Note in the top panel that persistent westerly 200 hPa wind anomalies during 1995 replaced the westerly anomalies that occurred throughout most of 1994. The 1994 pressure conditions were the highest of the last 50 years whereas the 1995 surface pressure was close to being the lowest of the last 50 years. That tropical cyclone conditions would be so different between these two seasons is no accident.

It has been known for many years that sea level pressure is associated with powerful modifications of seasonal hurricane activity. The very active hurricane years of 1969, 1961, 1955, 1950 and 1933 were also years of very low western tropical Atlantic surface pressure. Much of the influence of surface pressure is associated with vertical wind shear, tropospheric moisture and low-level divergence.

Some may argue that the August-October surface pressure differences were a result of the cyclones themselves and not environmental differences. This is not true as tropical cyclones neither cover a large enough area nor last long enough to be responsible for the very low surface pressures observed during the 1995 hurricane season - only a small portion of this pressure drop may be so explained. No tropical cyclones came close to the measurement stations of Trinidad, Curacao, and Cayenne.

THE 1995 HURRICANE SEASON AND GLOBAL WARMING

Some individuals will interpret the great upswing in 1995 hurricane activity as related in some way to increased man-induced greenhouse gases like carbon dioxide (CO\(_2\)). Such individuals are sometimes driven more from a political than a scientific agenda. There is no reasonable way that such an interpretation can be made. Man-induced greenhouse gas warming, even if a physically valid hypothesis, is a very slow and gradual process that, at best would only be expected to bring about small changes in global circulation over periods of 50 to 100 years. Not the abrupt and dramatic one year upturn in hurricane activity as occurred between 1994 and 1995. And, even if man induced greenhouse increases over the last 25 years were to be interpreted as causing global mean temperature increase over the last 25 years, there is no way to relate such small global temperature increases to intense Atlantic basin hurricane activity during this period. Atlantic intense (or category 3-5 hurricane activity) has shown a substantial decrease to only about 40 percent of the amount of intense hurricane activity which occurred 25-50 years ago. Intense hurricane activity in the Atlantic basin has shown a significant decrease while the globe has undergone a small mean temperature increase. We interpret most of this global mean temperature increase as resulting from natural and not from man-induced influences. The large increase in 1995 Atlantic hurricane activity is no mystery. It was the results of natural variations in global circulation patterns and we were able to predict a portion of this increase without invoking global warming or greenhouse gas increases. Therefore, "there is no plausible way that increases in man-induced greenhouse gases can be even remotely related to this year's extremely active Atlantic basin hurricane season".

VERIFICATION OF AUTHORS' FORECAST OF THE 1995 HURRICANE SEASON

All of our 1995 hurricane forecasts were for an above average season. Our forecast of named storm days, hurricane days, and intense or major hurricane days, although calling for an above average season of all parameters, did not well specify how unusually active this season would become. Tables 12 and 13 show our 1995 hurricane forecasts for total seasonal activity which were issued on 30 November 1994, and 7 June 1995. Table 14 shows how our 4 August 1995 forecast of hurricane activity after 1 August 1995 has verified (see Gray et al. 1995a, 1995b). The first author made a qualitative adjustment to the 30 November 1994 forecast at the National Hurricane Conference in Atlantic City on April 14, 1995. This was based on a then false assessment of March ENSO and Atlantic sea surface temperature conditions. This qualitative downward adjustment of the 30 November 1994 forecast is also shown in Table 12. This was a mistake that will not be repeated; no qualitative adjustments to our forecasts will henceforth be made in the future. We are now planning to make a new seasonal hurricane forecast in early April which will be quantitatively based on meteorological data through March.

Despite our underprediction of the unusually high amounts of 1995 tropical cyclone activity, we were quite correct in anticipating a great upswing in 1995 activity from the very inactive 1991-94 seasons. We also correctly forecast the 1995 dissipation of the El Nino in November 1994. This was contrary to most El Nino forecasts of the time and most of those into the winter and spring of 1995. Here are a few excerpts from our forecast write-up of the 1995 season.

From our 30 November 1994 forecast.
Table 12: Verification of our 1995 total seasonal hurricane predictions.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Named Storms (NS)</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>Named Storm Days (NSD)</td>
<td>65</td>
<td>65</td>
</tr>
<tr>
<td>Hurricanes (H)</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>Hurricane Days (HD)</td>
<td>35</td>
<td>35</td>
</tr>
<tr>
<td>Intense Hurricanes (IH)</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Intense Hurricane Days (IHD)</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>Hurricane Destruction</td>
<td>100</td>
<td>110</td>
</tr>
<tr>
<td>Potential (HDP)</td>
<td>140</td>
<td>140</td>
</tr>
</tbody>
</table>

Table 13: Verification of 4 August 1995 forecast for hurricane activity after 1 August.

<table>
<thead>
<tr>
<th>Forecast Parameter</th>
<th>After Aug 1 Verification</th>
<th>After Aug 1 Forecast Activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Named Storms (NS)</td>
<td>7.8</td>
<td>11</td>
</tr>
<tr>
<td>Named Storm Days (NSD)</td>
<td>41.4</td>
<td>49</td>
</tr>
<tr>
<td>Hurricanes (H)</td>
<td>5.1</td>
<td>7</td>
</tr>
<tr>
<td>Hurricane Days (HD)</td>
<td>21.4</td>
<td>27</td>
</tr>
<tr>
<td>Intense Hurricanes (IH)</td>
<td>2.0</td>
<td>3</td>
</tr>
<tr>
<td>Intense Hurricane Days (IHD)</td>
<td>4.4</td>
<td>5</td>
</tr>
<tr>
<td>Hurricane Destruction</td>
<td>64.4</td>
<td>84</td>
</tr>
<tr>
<td>Potential (HDP)</td>
<td>86.0</td>
<td>107</td>
</tr>
</tbody>
</table>

"The 1995 season should be much more active than the four recent 1991 through 1994 hurricane seasons, and especially in the tropical regions at latitudes south of 25°N where only two short lived hurricanes have occurred during the last four years. The character of 1995 season should tend toward that of the two recent hurricane seasons of 1988 and 1989 which produced a total of five intense or major hurricanes and 19 intense hurricane days".

"Implicit in this forecast is the anticipated dissipation of the long running equatorial Pacific warm water event which has now persisted for over four consecutive years. Our extended range ENSO prediction scheme forecasts a NINO-3 sea surface temperature anomaly of -0.7°C for the August-October 1995 period. The inhibiting influence on hurricane activity of warm equatorial Pacific water temperatures for next year is thus felt to be very low. Consequently, hurricane activity should be higher".

From our 5 June 1995 forecast.

"Past records indicate that it is typical to have a number of suppressed or somewhat below normal years in a row which are then followed by a year of greatly increased hurricane activity. It appears that 1995 will be one of those seasons wherein a large upsurge in hurricane activity occurs.

The El Nino, stratospheric QBO, West African rainfall, and Atlantic sea surface temperature anomalies are all coming together to promote the large-scale wind and thermal-moisture conditions which are associated with an active season.

The probability of hurricane activity within the Gulf of Mexico will be higher during 1995 than it has been since 1989.

There has been no hurricane activity at all within the Caribbean during the last five years. This is a consequence of the long lasting El Nino event of 1991-94, Western Sahel drought conditions during 1990-93 and higher than average Caribbean basin surface pressures during the last five years. These inhibiting influences are not expected to be present during the 1995 season. Consequently, the probability of Caribbean basin hurricane activity will be greater this year than any of the last five years".

Table 14: Verification of 4 August 1995 forecast for total 1995 seasonal activity.

<table>
<thead>
<tr>
<th>Forecast Parameter</th>
<th>Last 45-Year Average</th>
<th>Forecast Total Seasonal Activity</th>
<th>Verification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Named Storms (NS)</td>
<td>9.3</td>
<td>16</td>
<td>19</td>
</tr>
<tr>
<td>Named Storm Days (NSD)</td>
<td>46.1</td>
<td>65</td>
<td>121</td>
</tr>
<tr>
<td>Hurricanes (H)</td>
<td>5.7</td>
<td>9</td>
<td>11</td>
</tr>
<tr>
<td>Hurricane Days (HD)</td>
<td>23.0</td>
<td>30</td>
<td>62</td>
</tr>
<tr>
<td>Intense Hurricanes (IH)</td>
<td>2.1</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>Intense Hurricane Days (IHD)</td>
<td>4.5</td>
<td>5</td>
<td>12</td>
</tr>
<tr>
<td>Hurricane Destruction</td>
<td>68.1</td>
<td>90</td>
<td>172</td>
</tr>
<tr>
<td>Potential (HDP)</td>
<td>100</td>
<td>130</td>
<td>237</td>
</tr>
</tbody>
</table>

From our 4 August 1995 forecast.

"Most of those global and regional meteorological features which in the past have been associated with active Atlantic hurricane seasons are coming
together this summer. There is a very high statistical probability that 1995 will experience a very active hurricane season".

**SCHEDULE OF ATLANTIC BASIN SEASONAL HURRICANE FORECASTS FOR 1996**

A seasonal forecast for the 1996 hurricane season will be issued on 30 November 1995 with regular updates coming on 5 April 1996, 6 June 1996, and 7 August 1996. A 1996 seasonal verification and a forecast of 1997 hurricane activity will be issued in late November 1996. In addition, seasonal forecasts of late summer and fall 1997 ENSO conditions, the anticipated 1997 Sahel rainfall conditions will also be issued in late November, 1996.

**ACKNOWLEDGEMENTS**

The authors are indebted to a number of meteorological experts who have furnished us with the data necessary to make this forecast or who have given us valuable assessments of the current state of global atmospheric and oceanic conditions. We are particularly grateful to John Sheaffer and John Knaff for their very penetrating climate discussions and data inputs. We are also grateful to Colin McAdie who has furnished much data necessary to make this forecast and to Vern Kousky, Gerry Bell, James Angell and Richard Larson for helpful discussion. The authors have also profited from in-depth interchange with his project colleagues Ray Zehr, Patrick Fitzpatrick and James Kossin. William Thorson and Richard Taft have provided valuable computer assistance. We wish to thank Tom Ross of NCDC, Wassila Thiao and Vadlamani Kumar of the African Desk of CPC who provided us with West African and other meteorological information. Douglas LeCompte of USDA has provided us with continuous African rainfall summaries. Barbara Brumit and Arnie Hedstrom have provided manuscript and data reduction assistance. We appreciate receiving the UK Meteorological Office experimental forecasts of this summer's Sahel precipitation. We have profited over the years from many in-depth discussions with most of the current NHC hurricane forecasters. These include Lixion Avila, Miles Lawrence, Max Mayfield, Richard Pasch and Edward Rappaport. The first author would further like to acknowledge the encouragement he has received over recent years for this type of forecasting research applications from Neil Frank and Robert Sheets, the former directors of the National Hurricane Center (NHC) and from Jerry Jarrell, Deputy NHC director. We look forward to a beneficial association with the new director, Robert Burpee.

This research analysis and forecast has been supported by research grants from the National Science Foundation (NSF) and National Atmospheric and Oceanic Administration (NOAA) National Weather Service and Climate Prediction Center.

**REFERENCES**

Aagaad, K., 1995: The fresh water flux through Fram Strait: A variable control on the thermohaline circulation. NOAA sponsored Atlantic climate conveyor belt project meeting, 2-4 May, Miami, FL.


**APPENDIX A:**

**DERIVED MEASURES OF SEASONAL HURRICANE ACTIVITY**

Measures of seasonal tropical cyclone activity include the seasonal total number of named storms (NS), hurricanes (H), intense (or major) hurricanes (IH), named storm days (NSD), hurricane days (HD), intense hurricane days (IHD), and hurricane destruction potential (HDP). Definitions of these hurricane indices are given at the beginning of this report. More detailed information is contained in Gray *et al.* (1992, 1994) and in Landsea (1993). In view of this complexity, it is desirable to define a single number which provides a simple but comprehensive expression of net season tropical cyclone activity in terms of a percentage difference from a long term mean. To this end, we propose a new parameter of seasonal activity termed the "Net Tropical Cyclone activity" (NTC) which is defined as:

\[
NTC = \frac{(\%NS + \%H + \%IH + \%NSD + \%HD + \%IHD)}{6}
\]

where each of six of the percentage departure values from the long term means are used as measures of seasonal activity. The NTC value is useful as a measure of seasonal tropical cyclone activity because it combines most of the other tropical cyclone parameters of interest into a single index. There are many seasons during which a single parameter, say for example, the number of hurricanes, is not well representative of the actual character of the overall tropical cyclone activity for that year. This single index has the highest forecast skill. Table 16 lists the values of NTC for 1950-1994.

**Table 16: Listing of Seasonal Net Tropical Cyclone activity (NTC) values between 1950-1995.**

<table>
<thead>
<tr>
<th>Year</th>
<th>NTC(%)</th>
<th>Year</th>
<th>NTC(%)</th>
<th>Year</th>
<th>NTC(%)</th>
<th>Year</th>
<th>NTC(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1950</td>
<td>243</td>
<td>1962</td>
<td>33</td>
<td>1974</td>
<td>76</td>
<td>1986</td>
<td>38</td>
</tr>
<tr>
<td>1951</td>
<td>121</td>
<td>1963</td>
<td>116</td>
<td>1975</td>
<td>92</td>
<td>1987</td>
<td>48</td>
</tr>
<tr>
<td>1952</td>
<td>97</td>
<td>1964</td>
<td>168</td>
<td>1976</td>
<td>85</td>
<td>1988</td>
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<td>1966</td>
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<td>1978</td>
<td>86</td>
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<td>1960</td>
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<td>1972</td>
<td>28</td>
<td>1984</td>
<td>77</td>
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<tr>
<td>1961</td>
<td>222</td>
<td>1973</td>
<td>52</td>
<td>1985</td>
<td>110</td>
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</tr>
</tbody>
</table>

Other measures of seasonal tropical cyclone activities include Hurricane Destruction Potential (HDP) and Maximum Potential Destruction (MPD). HDP is expressed in 10^4 knots^2, MPD in 10^3 knots^2. Table 17 includes these values over the last 46-year period.
### Table 17: Hurricane Destruction Potential (HDP) and Maximum Potential Destruction (MPD) between 1950-1995.

<table>
<thead>
<tr>
<th>Year</th>
<th>HDP</th>
<th>MPD</th>
<th>Year</th>
<th>HDP</th>
<th>MPD</th>
<th>Year</th>
<th>HDP</th>
<th>MPD</th>
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</thead>
<tbody>
<tr>
<td>1950</td>
<td>200</td>
<td>130</td>
<td>1957</td>
<td>66</td>
<td>46</td>
<td></td>
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<td>1951</td>
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<td>94</td>
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<td>1952</td>
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<td>81</td>
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<td>1954</td>
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<td>1961</td>
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<td>1965</td>
<td>73</td>
<td>38</td>
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</tr>
</tbody>
</table>

The rainy season in North Africa's Sahel occurs almost exclusively during the months of June through September when the inter-tropical convergence zone (ITCZ) reaches its farthest northward extension. The Sahel is defined here as the North African region between 10 and 20°N. It is this area which has experienced persistent droughts during the last three decades. This report provides a verification of 1995 Sahelian seasonal rainfall forecasts issued in early December 1994 and early June 1995 and presents an extended range forecast for next year's June to September 1996 seasonal forecast for the Sahel based on data available through late November.

Because of rainfall variability within the region, a single homogeneous index of precipitation cannot be utilized for the entire Sahel. Instead, two smaller subregions are delineated within each of which precipitation shows fairly coherent seasonal behavior. These two regions are termed the "West" and "Central" Sahel. (Previously, a third region - the East Sahel - was utilized, but this area is no longer being considered due to the intrinsic inhomogeneity of its rainfall characteristics). The West Sahel extends from the Atlantic coast to longitude 6°W including portions of Mauritania, Senegal, Gambia, Guinea-Bissau, Guinea, and Mali. The Central Sahel is the region from 6°W to 20°E and includes parts of Mali, Burkina Faso, Ghana, Togo, Benin, Niger, Nigeria, Cameroon, Chad, Central African Republic, and Sudan. Note that the Central Sahel is more than twice the size of the West Sahel.

**JUNE TO SEPTEMBER RAINFALL IN THE AFRICAN SAHEL: VERIFICATION OF OUR 1995 FORECASTS AND AN EXTENDED RANGE FORECAST FOR 1996**

By Christopher W. Landsea*, William M. Gray**, Paul W. Mielke, Jr.***, and Kenneth J. Berry****

Department of Atmospheric Science
Colorado State University
Fort Collins, CO 80523

* NOAA Post-Doctorate Fellow in Climate and Global Change, NOAA AOML/ Hurricane Research Division
Internet: landsea@aoml.noaa.gov

** Professor of Atmospheric Science

*** Professor of Statistics

(As of 30 November 1995)
**Table 1: Summary of 1995 Sahel Rainfall Forecasts.**

<table>
<thead>
<tr>
<th>Region</th>
<th>1 December Forecast</th>
<th>6 June Update</th>
</tr>
</thead>
<tbody>
<tr>
<td>West Sahel</td>
<td>+0.34 S.D. (WET)</td>
<td>+0.27 S.D. (WET)</td>
</tr>
<tr>
<td>Central Sahel</td>
<td>+0.17 S.D. (WET)</td>
<td>+0.30 S.D. (WET)</td>
</tr>
</tbody>
</table>

**Table 2: Threshold values (expressed in SD) for quintile seasonal precipitation categories as shown.**

<table>
<thead>
<tr>
<th>Region</th>
<th>Very Dry (8 years)</th>
<th>Dry (8 years)</th>
<th>Neutral (8 years)</th>
<th>Wet (8 years)</th>
<th>Very Wet (8 years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>West Sahel</td>
<td>-1.35/-0.75</td>
<td>-0.74/-0.32</td>
<td>-0.31/+0.26</td>
<td>+0.27/+0.61</td>
<td>+0.62/+1.28</td>
</tr>
<tr>
<td>Central Sahel</td>
<td>-1.55/-0.63</td>
<td>-0.62/-0.15</td>
<td>-0.14/+0.11</td>
<td>+0.12/+0.64</td>
<td>+0.65/+1.13</td>
</tr>
</tbody>
</table>

Thus, the forecasts originally issued in early December 1994 were just within the low end of the WET quintile calling for above average rainfall conditions for both the West and Central Sahel. The early June forecasts kept the West Sahel nearly the same and pushed the Central Sahel into the middle of the WET category. Note that these were forecasts for conditions quite different conditions from what has been seen in recent years. In particular, during for the last 25 years nearly three-quarters of the years have been DRY to VERY DRY in the Sahel.

Based upon new 1995 data received to date (we gratefully acknowledge the data provided by Wassila Thiao and Rich Tinker at the U.S. Climate Prediction Center and Tom Ross at the U.S. National Climate Data Center), the Sahel region experienced DRY conditions in the Central Sahel and NEUTRAL conditions in the West Sahel. Table 3 provides a month-by-month breakdown of 1995 rainfall variability. To provide comparisons of 1995 versus other years, Table 3 also provides a listing of June to September periods that were most similar to rainfall amounts occurring in 1995. The top row of numbers in Table 3 indicate the rainfall standardized deviations and the lower numbers indicate the number of stations reporting in the region that were below average/near average/or above average, respectively. Compared to the forecasts, observed conditions were drier than anticipated. One quintile West Sahel prediction errors were observed whereas Central Sahel predictions were two quintiles off. Overall the forecasts for 1995 may be judged as marginally successful for the West Sahel and not very good for the Central Sahel.

**Table 3: Summary of observed 1995 monthly Sahel rainfall. Number of stations reporting (below/near/above) averages are also indicated as such.**

<table>
<thead>
<tr>
<th>Region</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Jun-Sep</th>
</tr>
</thead>
<tbody>
<tr>
<td>West</td>
<td>-0.44</td>
<td>-0.16</td>
<td>-0.28</td>
<td>-0.11</td>
<td>-0.29</td>
</tr>
<tr>
<td>Central</td>
<td>-0.23</td>
<td>-0.46</td>
<td>-0.08</td>
<td>-0.38</td>
<td>-0.55</td>
</tr>
</tbody>
</table>

**Table 4: Analog years with rainfall totals near those observed during 1996.**

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>West</td>
<td>-0.29</td>
<td>0.37</td>
<td>0.25</td>
<td>0.27</td>
<td>0.37</td>
<td>0.27</td>
<td>0.37</td>
</tr>
<tr>
<td>Central</td>
<td>-0.65</td>
<td>0.48</td>
<td>0.48</td>
<td>0.60</td>
<td>0.61</td>
<td>0.61</td>
<td>0.61</td>
</tr>
</tbody>
</table>

It was suggested by 1995 forecasts that WET conditions would likely arise due to a combination of several factors which indicated forthcoming near to wetter than average conditions. These factors included: 1) the West phase of the QBO (favorable for enhanced rainfall), 2) near to slightly wet conditions last year in the West Sahel and Gulf of Guinea region (thereby near neutral indicators), 3) (for the 6 June forecast) cool El Nino-Southern Oscillation (ENSO) conditions (moderate enhancing factor), and 4) (for the 6 June forecast) mixed pre-season West Africa surface temperature and pressure gradients (neutral factor). It is quite possible that the third factor - ENSO - failed to play a substantial role in the Sahel rainfall as significant distributions of cold equatorial Pacific SSTs (or La Nina) had not yet developed. Another consideration is the likely influence of very warm waters that appeared in the tropical South Atlantic Ocean this year. Previous research has shown that significant SST warming in this region is linked to dry conditions throughout the Sahel. Future Sahel forecasts (especially for the early June update) must attempt to incorporate this information into the predictive scheme.

One disturbing feature of the observed below average 1995 Sahel rainfall is that this trend was inconsistent with the concurrent active 1995
Atlantic hurricane season. Gray (1990) and Landsea and Gray (1992) showed that drought years in the West Sahel usually are accompanied by quiet Atlantic hurricane seasons, especially for intense hurricane activity. It turns out that 1995 was a near-record year for Atlantic hurricanes: 19 named storms, 11 of these becoming hurricanes, and 5 of those reaching intense (Saffir-Simpson category 3-4-5) hurricane status. While 1995 was not a drought year in the West Sahel, the value of -0.29 is in the low end of the NEUTRAL quintile and is not consistent with what happened with the hurricane activity. It may be that other factors can enhance the Atlantic hurricane activity while being fairly insensitive to Sahel rainfall. Preliminary work suggests that the Caribbean Sea region sea level pressures and/or sea surface temperatures may be this factor. Regardless, a small consolation here is that, once again, the West Sahel had rainfall anomalies which were better related to the hurricane activity than was the Central Sahel rainfall. In particular, Table 5 provides a summary of the observed values of June to September rainfall and associated quintile value (V,W,N,D,VD) along with the number of intense hurricane days (IHD) from 1988-1995:

<table>
<thead>
<tr>
<th>Year</th>
<th>IHD</th>
<th>West Sahel</th>
<th>Central Sahel</th>
</tr>
</thead>
<tbody>
<tr>
<td>1988</td>
<td>8.0</td>
<td>+ .25/N</td>
<td>+ .09/N</td>
</tr>
<tr>
<td>1989</td>
<td>10.8</td>
<td>+ .27/W</td>
<td>- .16/D</td>
</tr>
<tr>
<td>1990</td>
<td>1.0</td>
<td>.91/VD</td>
<td>- .96/VD</td>
</tr>
<tr>
<td>1991</td>
<td>1.2</td>
<td>- .86/VD</td>
<td>- .19/D</td>
</tr>
<tr>
<td>1992</td>
<td>3.2</td>
<td>- 1.05/VD</td>
<td>- .48/D</td>
</tr>
<tr>
<td>1993</td>
<td>0.8</td>
<td>- .80/VD</td>
<td>- .60/D</td>
</tr>
<tr>
<td>1994</td>
<td>0.0</td>
<td>- .27/N</td>
<td>+ .74/VW</td>
</tr>
<tr>
<td>1995</td>
<td>12.0</td>
<td>- .29/N</td>
<td>- .55/D</td>
</tr>
</tbody>
</table>

STATISTICAL METHODOLOGY AND 1996 FORECAST

The techniques used in making these seasonal precipitation forecasts are detailed in full in Landsea et al. (1993) and Gray et al. (1992, 1993, 1994). Briefly, we use a Least Absolute Deviations (LAD) regression procedure instead of the traditional Ordinary Least Squares (OLS) multiple regression based upon the years 1950 to 1994. LAD is preferable over OLS in that LAD methodology is based upon minimizing the absolute linear differences between predicted and observed values instead of the square of the difference. In this approach, outliers do not overly influence the prediction equations. The amount of skill is estimated by regression on the entire data set with a standard degradation applied (as detailed in Mielke et al. 1995). In general, degradation increases with the number of predictors and decreases with the number of years under consideration. Five predictors are constructed via the LAD regression in a linear model to make the forecast. The five predictors which provide optimum long lead skill are linked to the stratospheric Quasi-Biennial Oscillation (QBO) and previous year North African rainfall data. The individual predictors and specific values to be used as input for the 1996 forecast are as follows:

**QBO Predictors:**
- Zonal (U) winds at 50 hPa observed at 10°N = -20 ms⁻¹ (extrapolated to Sep. 1996)
- Zonal (U) winds at 30 hPa at 10°N = -24 ms⁻¹ (extrapolated to Sep. 1996)
- Vertical shear of the zonal wind between 30 and 50 hPa = 4 ms⁻¹ (extrapolated to Sep. 1996)

**North African Predictors:**
- Aug-Sep 1995 West Sahel rainfall = -0.35 S.D.
- Aug-Nov. 1995 Gulf of Guinea rainfall = +0.09 S.D.

A new, experimental methodology is also being tested which chooses a total of six predictors from a total pool of nine potential predictors (i.e., the above five plus four additional). The four new potential predictors are as follows:

- Jun-Aug. Zonal (U) winds at 50 hPa at 10°N = - 9 ms⁻¹ (no extrapolation)
- Jun-Sep West Sahel rainfall 1992-1995 average = -0.59 S.D.
- Nov North Atlantic surface ridge position = 0.0 S.D.
- Mar-Aug Singapore 100 hPa T anomaly = -0.39°C

The above predictor values are based upon information available to us at CSU at the end of November 1995. Using these input data, the statistical models predict the rainfall values for June-September 1996 listed in Table 6. A subjective interpretation of these statistical forecasts yields our final forecast of 0.00 S.D. (NEUTRAL quintile) or “average” rainfall for both the West and Central Sahel for June to September 1996. These forecasts for near
average conditions in both the West and Central Sahel then correspond to conditions similar to the years 1963 (West Sahel -.25 S.D. and Central Sahel +.05 S.D.), 1974 (-.09 and -.03), and 1978 (-.10 and -.03). Note that while the West and Central Sahel often have similar rainfall anomalies, there are also several years wherein this is not the case. The 1994 rainfall anomalies provided an excellent example of the latter wherein the West Sahel experienced NEUTRAL rainfall conditions while the Central Sahel was in the VERY WET quintile.

Table 6: Sahel 1996 rainfall forecasts using both prior (first column) and revised-current methodology (second column).

<table>
<thead>
<tr>
<th></th>
<th>Previous Method</th>
<th>New Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>West Sahel</td>
<td>- 0.06 S.D. (NEUTRAL)</td>
<td>+0.03 S.D. (NEUTRAL)</td>
</tr>
<tr>
<td>Central Sahel</td>
<td>+0.06 S.D. (NEUTRAL)</td>
<td>0.00 S.D. (NEUTRAL)</td>
</tr>
</tbody>
</table>

The forecast of near average forecast values for Sahel rainfall during 1996 are due to 1) a near neutral factor associated with the QBO wherein a strong east phase (slightly inhibiting rainfall) together with a small wind shear between 30 and 50 hPa (slightly enhancing rainfall) expected next summer; 2) slightly dry August through September conditions the West Sahel (and moderately dry for June through September during the past four years) indicating the possibility of dry conditions based upon persistence; 3) near average rainfall along the Gulf of Guinea during August through November 1995 which suggests that the continental evaporation/evapotranspiration moisture source will provide near average moisture for the Sahel next year; 4) slightly cool Singapore 100 hPa temperatures, indicating that relatively cool El Nino-Southern Oscillation (ENSO) conditions are likely to prevail next summer and thus enhancing the Sahel rainfall; and 5) near normal position of the North Atlantic ridge suggesting near average sea surface temperatures will occur next summer over the tropical Atlantic also indicating near average rainfall. Thus, in combination, the two Sahel regions are forecast for near average rainfall conditions June through September 1996 and a drought year appears highly unlikely.

A crucial item for the forecast is the El Nino-Southern Oscillation (ENSO) phase which will be present next summer and fall. Some coupled numerical model studies have suggested that a major El Nino event may occur by late summer - early fall 1995 (Barnston 1995). Major El Nino events have previously been linked to drought conditions in the Sahel, especially the West Sahel. However, currently a moderate cooling has been occurring and, if this trend continues, a significant La Nina (or cold phase of ENSO) may be in place by summer 1996. If so, an enhancement of the Sahel rainfall, especially in the West Sahel region, may occur. Thus the ENSO parameters will have to be closely monitored over the next several months.

The other factor which apparently compromised the 1995 seasonal forecasts was strong surface warming in the tropical South Atlantic which may have contributed toward the Sahel being drier than anticipated. We must include this factor in the statistical forecasting methodology for the early June forecast update. The amount of skill indicated in the hindcast testing of the five predictors during the years 1950 to 1991 is for 56% of the variability in both the West and Central Sahel. Recent tests (Mielke et al. 1995), however, have suggested that the true skill that would be found in independent data would be on the order of 38%. This translates to standard errors of around +/- 0.25 S.D. or just less than a quintile category. Note that simple use of only persistence provides just 25% and 32% for the two regions, respectively.

An updated forecast will be provided in early June 1996 at the beginning of the Sahel rainy season, which will use updated QBO, ENSO, and African land surface data (and hopefully South Atlantic sea surface temperature information). A verification of these forecasts will be done by late November of 1996.

REFERENCES


**EXTENDED RANGE PREDICTION OF ENSO CONDITIONS (NINO-3 SST ANOMALY) FOR THE PERIOD OF AUGUST 1996 TO FEBRUARY 1997 AND VERIFICATION OF LAST YEAR'S FORECAST**

(Cool conditions are expected to continue through 1996)


Department of Atmospheric Science
Colorado State University
Fort Collins, CO 80523

* Professor of Atmospheric Science
** Advanced Ph.D. Student, Atmospheric Science
*** Professor of Statistics

[Various long and short versions of this forecast with figures and tables are available on the Wide World Web at this URL (http://typhoon.atmos.colostate.edu/forecasts/index.html)]

(As of 30 November 1995)

**ABSTRACT**

This brief discussion provides forecast statistics plus an overview of extended range forecast scheme for predicting the equatorial East Pacific Sea Surface Temperature Anomalies (SSTA) in the Nino-3 region. We use these schemes to make forecasts of Nino-3 SSTA for the period of August to October 1996 and November 1996 through January 1997. Our forecast calls for a negative sea surface temperature anomalies to continue through 1996.

**El Nino-Southern Oscillation - Background**

In recent years the authors have been working to develop a method for the extended range prediction of equatorial East Pacific Nino-3 Sea-surface Temperature Anomaly (SSTA). Using predictors available by late November of the previous year, we make SSTA forecast for August through October and November-January of the following year. It appears that we have developed a couple of very skillful empirical schemes to do this, particularly considering the extended range of the forecast and the difficulties innate to making such an extended range forecast.

The physical principles and philosophy behind this forecast are explained by several papers listed in the references.

**Forecasting Techniques**

We have developed two ENSO prediction schemes. The first scheme was developed three years ago, the second scheme is now in the final stages of development.

**Our First ENSO Forecast Scheme.**

This is based on an optimum combination of multiple lag relationships observed between variations of Nino-3 SST and a number of climate indices. We have made extensive tests of these predictors for a 34-year base data period extending from 1959 through 1992. The principal temporal limit imposed on the data period (i.e., after 1958) is due to the availability of 100 hPa temperature data at Singapore. Our analysis has yielded an optimized regression equation.
(Equation 1) for the most skillful set of extended range hindcasts. The prediction uses six derived coefficients \(a_1 \ldots a_6\) alone with the current observed values for the six predictors which are available during the fall time frame to make timely ENSO forecasts for the subsequent year. Through both physical reasoning and trial and error, we find that the following parameters, when taken together, yield a surprisingly high degree of skill for extended range hindcasts of Nino-3 SST anomalies.

Details of these forecast parameters and the rationale for their use in ENSO prediction are as follows:

\[
\text{Nino-3} = a_1(U_{\text{QBO}}) + a_2(T_A_1) + a_3(T_A_2) + a_4(P_{\text{TA}}) + a_5(N_{3_{27}}) + a_6(R_s) \\
\text{(1)}
\]

Symbols are defined below:

1. Nine-month forward extrapolated (November to September) stratospheric QBO zonal wind anomalies at 50 hPa (18 Ian) and at 30 hPa (23 Ian) plus the resulting absolute vertical shear of the zonal wind between these levels: \(\Delta U_{\text{QBO}}\).

More deep convection typically occurs near the equator (0-7° latitude) during the QBO east phase whereas enhanced off-equator (8-15° latitude) deep convection typically occurs during QBO west phase conditions (see Gray et al. 1992, Sheaffer and Gray 1993, Knaff 1993).

2. Singapore 100 hPa temperature anomaly values during the prior September through February \(T_{A1}\) and March through August \(T_{A2}\) Periods:

The implications of variable 100 hPa temperatures at Singapore are discussed in another report (see Sheaffer and Gray 1994); basically, anomalous 100 hPa temperatures reflect convective processes tied to trends in the heat content of the Pacific Warm Pool ocean surface layer, and hence, contain information concerning the possible intensity of forthcoming warm events.

3. Darwin SLPA during the prior May through July \(P_{s}\):

This index provides a good measure of the tropospheric biennial oscillation (QB); when low in one year, the QB tends to be high the next year (see Meehl, 1987; Rasmussen et al., 1991). Darwin May to July SLPA indicate the strength of the Tarawa (1.5°N, 173°E) surface winds during the following year which are related to ENSO variations. When Darwin SLPA is higher than normal during the prior May through July, then West Pacific (i.e., Tarawa) easterly equatorial surface trade winds are typically stronger than normal (negative zonal wind anomaly) during the following year June through November period. This linkage tends to lead to future cold ENSO conditions. The opposite set of associations occurs when prior May through November Darwin SLPA were lower than normal.

4. Prior 27-month NINO-3 SSTA \(N_{3_{27}}\):

This index provides a measure of recent ENSO conditions in the eastern Pacific SST. Warm and cold water conditions are not maintained for long periods. If the prior two-year NINO-3 SSTA conditions have been cold, then they will likely change to warm conditions during the next year and vice versa. This is a purely empirical relationship which offers important predictive information.

5. West African Rainfall \(R_s\):

An index of August-September rainfall from 38 stations in the Western Sahel region of West Africa also gives useful information for the following year's NINO-3 SSTA prediction. This predictive relationship involves a negative association between Western Sahel rainfall and Nino-3 SSTA. This measures the QB nature of the atmosphere and the multi-decadal changes.

We have two forecast developmental data sets for this earlier forecast procedure, one was made on the 34-year period of 1959-1992, and the other on the 37-year period of 1959-1995.

Specific values for the six forecast parameters used to compute our 1996 ENSO forecast are as follows:

\[
\begin{align*}
1. \Delta U_{\text{QBO}} & = 4 \text{ ms}^{-1} \\
2. R_{s} & = -0.35 \text{ S.D.} \\
3. P_{\text{TA}} & = +4.33 \text{ hPa} \\
4. T_{A1} & = -11.67 \times 10^{-1} \text{ °C} \\
5. T_{A2} & = -3.9 \times 10^{-1} \text{ °C} \\
6. N_{3_{27}} & = +17.4 \times 10^{-2} \text{ °C}
\end{align*}
\]

When these numbers are plugged in our two forecast equations, we obtain the predictions for Nino-3 SSTA shown in Table 1.

These forecasts show non-cross validated hindcast skill ranging from 0.55 to 0.73. The expected degradation with independent data sets is estimated to be between 0.15-0.20, giving an
expected real forecast skill (or the amount of real variance explained) of 40 to 50 percent.

Table 1: Anticipated 1996 Nino-3 SSTA\textsubscript{s} obtained with basic forecast methods.

<table>
<thead>
<tr>
<th>Predicted Nino-3 SSTA in °C</th>
<th>from 1959-92</th>
<th>from 1959-95</th>
</tr>
</thead>
<tbody>
<tr>
<td>Developmental</td>
<td>Developmental</td>
<td></td>
</tr>
<tr>
<td>Data Set</td>
<td>Data Set</td>
<td></td>
</tr>
</tbody>
</table>

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>V1 (SSTA Aug-Oct 1996)</td>
<td>-0.70</td>
<td>-0.56</td>
</tr>
<tr>
<td>V2 (SSTA Nov 1996-Jan 1997)</td>
<td>-1.06</td>
<td>-0.85</td>
</tr>
<tr>
<td>V3 (SSTA Aug 1996-Jan 1997)</td>
<td>-0.86</td>
<td>-0.72</td>
</tr>
</tbody>
</table>

Recent Innovations

A recently developed forecast scheme involves the use of two separate pools of physically determined potential Nino-3 predictors. We use an IMSL "leaps and bounds" statistical regression procedure to explore and determine the best six predictors from which we then develop forecast regression equations. These two groups of pooled forecast predictors are

Table 2: Predictor values for 1996 "leaps and bounds" forecast methodology.

<table>
<thead>
<tr>
<th>Pool 1</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1 = (U_{90}) 9-month extrapolated QBO at 50 hPa</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 = (R_s) Sahel Aug-Sep rain in SD</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 = (R_s) Gulf of Guinea rain in SD</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4 = Darwin SLPA (May-Jul)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 = Singapore 100 hPa T4 (Mar-Aug)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 = Singapore 100 hPa T4 (Jul-Nov)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7 = Atlantic Ridge pressure between 20-30\textdegree W</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8 = Singapore minus Darwin SLPA (Jul-Nov)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9 = Balboa 50 hPa QBO (Jun-Aug)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Pool 2

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1 = (U_{90}) 9-month 50 mb</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 = (U_{90}) 9-month extrapolated 30 hPa</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 = (\bar{U}<em>{90}) \bar{U}</em>{90} 4-year Average</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4 = Guinea rainfall 4-year Average</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 = Atlantic Ridge</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 = Singapore 100 hPa T4 (Jul-Nov)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7 = Nino-3 (prior 27 months)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8 = Darwin SLPA (May-Jul)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9 = Calcutta SLPA (Aug-Nov)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

We have used these pooled predictors to develop forecast regression equations for Nino-3 forecasts for the periods of 1959-1995 and 1950-1995. We find that we can explain about 50-60 percent of variations in the non-degraded hindcast analysis of Nino-3 SSTA at 9-14 month lead time. These results appear to be superior to our older scheme. We have, however, not studied these results in sufficient detail to discuss specific numerical results. Concerning forecasts of what is going to happen in 1996, we note these two pools of ENSO predictors indicate August 1996 to January 1997 Nino-3 SSTA values of between -0.80 to -1.2 °C. Presumably, we feel that these predicted cooling values may be too strong. But whether or not such strong cooling will emerge next year or not, these recent forecast calculations support of our basic forecast scheme and indicate that a warm ENSO event in 1996 is unlikely.

1996 ENSO Forecast and Discussion

From qualitative assessment of predictions for 1996 from both our earlier and more recent revised ENSO forecasting methods, we judge it prudent to tone down our numerical predictions a bit and issue 1996 Nino-3 sea surface temperature anomaly (SSTA) forecasts as follows:

- August-October 1996: -0.6 °C
- November 96-January 1997: -0.8 °C

These forecasts strongly indicate that we do not expect a warm ENSO event to develop anytime during 1996. Despite the anticipated change over to easterly QBO wind anomalies early next year (easterly QBO winds favor ENSO warming) we expect that other regional conditions will inhibit the development of yet another summertime ENSO warming event as has during the summers of 1990 through 1994. Extended warm ENSO-like periods of 4-5 years tend to be followed by generally cold to neutral periods of a similar 4-5 years duration. We believe that we have just emerged from a 4-5 year warm ENSO event and are entering a period of alteration between cool and near neutral SST conditions.

A key indicator in this assessment is the cooling of Nino-4 SSTA's in recent months. On a climatological basis Nino-4 is the pace maker of the 5-year variations of ENSO in which the year to year oscillations operate. Nino-4 has gone negative for the first time since 1989 and we infer that a major alteration in ENSO conditions may be in the making. This yet another indication that cooler than normal conditions will prevail in 1996.
Verification of Last Year's ENSO Forecast for August-October 1995

Our 30 November 1994 ENSO forecast of last year called for August through October 1995 Nino-3 SSTA of -0.74 °C. The verification value of -0.57 °C is not far from our forecast. It is likely that the November 1995 through January 1996 SSTA forecast made last year will also show close agreement.

We note that most of the published ENSO forecasts from the Fall of 1994 to the Spring of 1995 called for warm ENSO conditions to persist through 1995. This has not occurred. Given the current cold conditions, our forecast of 30 November 1994 looks very good. It is to be noted that this apparently successful ENSO forecast was made without quantitative consideration of Pacific Ocean Kelvin and Rossby wave activity.

ACKNOWLEDGEMENTS

The authors acknowledge the very beneficial discussions and data assistance that they have had on this topic from John D. Sheaffer and Christopher W. Landsea. The ENSO related research on which these forecast methods are based has been supported by a US National Science Foundation Climate Research Grant.

BIBLIOGRAPHY


EXTENDED RANGE FORECAST OF ATLANTIC SEASONAL HURRICANE ACTIVITY FOR 1996

(A year of expected average hurricane activity)


* Professor of Atmospheric Science
** Post-doctoral fellow at NOAA/HRD Lab., Miami, FL
*** Professor of Statistics

Department of Atmospheric Science
Colorado State University
Fort Collins, CO 80523

HK Mets BULLETIN Vol. 5, No. 2, 1995

73
This forecast is based on ongoing research by the author and his Colorado State University and NOAA/IHRD research colleagues, together with meteorological information through late-November of 1995.

Various long and short versions of this forecast with figures and tables are available on the Wide World Web at this URL: http://typhoon.atmos.colostate.edu/forecasts/index.html

(As of 30 November 1995)

ABSTRACT

This paper presents details of a 6-11 month extended range seasonal forecast of the tropical cyclone activity likely to occur in the Atlantic Ocean basin during 1996. This forecast is based on a forecast scheme developed previously by the authors with several new modifications. This allows estimates of seasonal Atlantic tropical cyclone activity to be made by late November of the prior year. Our ever evolving forecast schemes are based on 10-month forward extrapolations of the stratospheric Quasi-Biennial Oscillation (QBO) of equatorial zonal winds, two measures of Western Sahel rainfall through late November 1995, an extended range forecast of El Nino conditions in August to October 1996, an extended range forecast of Western Sahel rainfall amount for next summer, the November strength of the Northeast Atlantic subtropical ridge and other forecast parameters from the Pacific Ocean and from the Asia-Australia area.

Information obtained through late-November 1995 indicates that 1996 Atlantic hurricane activity is likely to be somewhat below the 1950 to 1995 average with 5 hurricanes (average 5.7), 8 named storms (average 9.3), 40 named storm days (average 46), 20 hurricane days (average 23), 2 intense (category 3-4-5) hurricanes (average 2.1), 5 intense hurricane days (average 4.5) and a hurricane destruction potential (HDP) of 50 (average 68). Collectively, net tropical cyclone activity is expected to be 85 percent of the long period average. The 1996 season should be much less active than the four recent inactive hurricane seasons 1991 through 1994.

DEFINITIONS AND ABBREVIATIONS

Named Storm (NS) - A hurricane or tropical storm.
Named Storm Day (NSD) - Four consecutive six-hour periods during which a tropical cyclone is observed or estimated to have attained tropical storm or hurricane intensity winds.
Hurricane (H) - A tropical cyclone with sustained low level winds of 74 miles per hour (33 m/s or 64 knots) or greater.
Hurricane Day (HD) - Four six-hour periods during which a tropical cyclone is observed or estimated to have hurricane intensity winds.
Intense or Major Hurricane (IH) - A hurricane reaching sustained low level winds of at least 111 mph (96 kt or m/s) at some point in its lifetime. This constitutes a category three or higher storm intensity rating on the Saffir/Simpson scale.
Intense or Major Hurricane Day (IHD) - Four six-hour periods during which a hurricane has Saffir/Simpson category three intensity or higher.
Hurricane Destruction Potential (HDP) - A measure of a hurricane's potential for wind and storm surge destruction. HDP is defined as the sum of the square of a hurricane’s maximum wind speed during each six-hour period of its existence. This value is summed for the season and is expressed in units of 10^4 knots squared.
Net Tropical Cyclone Activity (NTC) - A combined measure of the average seasonal percentage of NS, NSD, H, HD, IH, and IHD to their long term mean.
Maximum Potential Destruction (MPD) - The seasonal sum of the square of the maximum wind in knots of each named storm in units of 10^6 knots squared. MPD is different than HDP because MPD gives only one value for each storm and does not contain information on the duration of the cyclone.

INTRODUCTION

Surprisingly strong long range predictive signals exist for Atlantic basin seasonal tropical cyclone activity. Our recent research indicates that a sizeable portion of the season-to-season variability of nine indices of Atlantic tropical cyclone activity can be skillfully hindcast by as early as late November of the prior year. We now have two separate prediction schemes for estimating hurricane activity in the following year. Information is developed from 46 years of past data (1950-1995). Our extended range predictive signals include two measures of Western Sahel rainfall during the prior year, the phase of the stratospheric Quasi-Biennial Oscillation of zonal winds at 30 hPa and 50 hPa (which can be extrapolated ten months into the future) and similar extended range predictions for El Nino-Southern Oscillation (ENSO) variability and Western Sahel rainfall anomalies for the following summer. A brief summary of these predictor indices is as follows:

a) QBO - Tropical Cyclone Lag Relationship
The easterly and westerly modes of stratospheric QBO zonal winds which circle the globe over the equatorial regions have a substantial influence on Atlantic tropical cyclone activity (Gray, 1984a; Shapiro, 1989). Typically, there is 50 to 75 percent more hurricane activity (depending on the specific activity index considered) during those seasons when stratospheric QBO winds between 30 and 50 mb are anomalously westerly and, consequently, when the vertical wind shear (i.e., the variation of wind speed with height) between these two levels is small. Conversely, seasonal hurricane activity is typically reduced when stratospheric QBO is in its easterly phase and the wind shear between 30 and 50 hPa is large. We project that 50 and 30 hPa winds will be strongly from the east next year with moderate shear between the two levels. This should then be an inhibiting influence on next year’s hurricane activity.

b) African Rainfall - Tropical Cyclone Lag Relationship

As discussed by Landsea (1991), Gray and Landsea (1992) and Gray et al. (1992), surprising strong predictive signals for seasonal hurricane activity can be obtained from rainfall data for Western Africa during the mid-summer to fall of prior year. These include:

1) August-September Western Sahel Rainfall. During the last four decades, the Western Sahel area has experienced large year to year persistence of rainfall trends; that is, wet years tend to be followed by wet years (e.g., in the 1950s and 1960s) while dry years are typically followed by dry years (e.g., in the 1970s, 1980s and 1990s). Since the rainfall in this region is positively related to Atlantic hurricane activity, persistence alone tends to provide a moderate amount of skill for forecasting next season’s African rainfall as well as the associated Atlantic hurricane activity. But, there are other non-persistent features which make this a useful forecast parameter.

2) August-November Rainfall in the Gulf of Guinea. Landsea (1991) and Gray and Landsea (1992) have documented an even stronger African rainfall - intense hurricane lag relationship using August through November rainfall along the Gulf of Guinea. Intense hurricane activity during seasons following the ten wettest August-November Gulf of Guinea years was four times greater than that which occurred during those hurricane seasons following the ten driest August-November periods in the Gulf of Guinea. This association suggests a very strong relationship between the following season’s hurricane activity and the August to November rainfall of the prior year. This year’s rainfall for the West Sahel during August-September 1995 was -0.35 S.D., somewhat dry. And the Gulf of Guinea August-November rainfall was somewhat above average (+0.14 S.D.). These trends and last years near average Sahelian rainfall indicate the long running Western Sahel drought conditions.

c) The El Nino-Southern Oscillation (ENSO) Lag Relationship

ENSO is one of the principal global scale environmental factors affecting Atlantic seasonal hurricane activity. Hurricane activity is usually much suppressed during those seasons when anomalously warm water temperatures are present in the equatorial eastern and central Pacific. And, activity is usually enhanced during seasons with cold (or La Nina) water conditions. Hurricane activity during the four seasons (1991-1994) was much suppressed because of persistent, warm water conditions in the Nino-3 and NINO-4 regions of the equatorial Pacific and the associated negative values of the Southern Oscillation Index (SOI or Tahiti minus Darwin surface pressure).

We have recently devised a scheme for making extended range predictions of next summer’s Nino-3 sea surface temperature anomaly (SSTA) conditions. This new ENSO prediction scheme (Gray et al. 1993) adds qualitative improvement to the extended range seasonal hurricane forecasts which Gray et al. (1992) developed previously but which lacked an ENSO prediction component. Nino-3 forecast for SSTA conditions for August through October 1996 is for cool water conditions. It appears that the four-year warm water event during 1991-1994 has definitely come to an end and we appear to be entering a new era of generally below normal eastern Pacific water temperatures. Cool ENSO conditions, much as was the case in 1995, should be an enhancing influence on next year’s hurricane activity.

d) Strength of the November Atlantic Subtropical Ridge Between 20-30W

The higher the surface pressure associated with this ridge, the stronger are the east Atlantic tradewinds which enhance upwelling of cold water off the northwest African coast. Colder surface water temperatures due to this enhanced ocean upwelling cause higher surface pressures and thus creates a positive feedback response. There is long term memory and feedback in this association. It is a useful parameter for predicting next year’s seasonal hurricane activity. The ridge strength this November was near the 1950
to 1995 mean and therefore neither inhibits or enhances 1996 hurricane activity.

e) Other Potential Long Range Predictors

Our analyses have also shown that other global parameters have some value for extended range Atlantic basin seasonal hurricane prediction and often improve our extended range forecasts. These include:

1. Singapore 100 hPa temperature anomalies during July to November,
2. Sea-surface temperature anomalies in the Nino-3 region of the equatorial Pacific during the prior 27 months,
3. Darwin, Australia sea-level pressure anomaly (SLPA) in the prior May-July period,
4. Calcutta, India SLPA in the prior September through November period.

With these, we have a total pool of 12 forecast parameters. From this group we choose the best 5 to 7 predictors for each individual tropical cyclone predictors through a leaps and bounds regression methodology. Our extended range forecast schemes are based on an optimized combination of multiple lag relationships between these forecast parameters and nine seasonal indices of tropical cyclone activity. Our forecast specifies the likely number of named storms (NS), named storm days (NSD), hurricanes (H), hurricane days (HD), intense hurricanes (IH), intense hurricane days (IHD), Hurricane Destruction Potential (HDP), net tropical cyclone activity (NTC), and Maximum Potential Destruction (MPD).

8-11 MONTH EXTENDED RANGE PREDICTION SCHEMES

Outline of Basic (Gray et al. 1992) Scheme

Our original extended range forecast scheme had the following form:

\[(\text{Seasonal Forecast}) = \beta_0 (1 + a_1 U_{50} + a_2 U_{30} + a_3 |U_{50} - U_{30}| + a_4 R_S + a_5 R_G)\]

where

1. \( U_{50} \) = 10 month extrapolated 50 hPa September QBO zonal wind near 10°
2. \( U_{30} \) = 10 month extrapolated 30 hPa September QBO zonal wind near 10°
3. \( |U_{50} - U_{30}| \) = 10 month extrapolated 50 hPa minus 30 hPa September QBO zonal wind shear
4. \( R_S \) = Measured standard deviation of previous year August-September West Sahel rainfall
5. \( R_G \) = Measured standard deviation of previous year August-November Gulf of Guinea rainfall

The \( \beta \) and "a" coefficients are determined to maximize the hindcast predictive signals. Different \( \beta \) and "a" coefficients are determined for each predictor. These equations were developed on data from the 41 years of 1950-1990. They explain about 40-50 percent of the variance of each of the nine forecast parameters in non-independent hindcasts.

Values of the forecast parameters used for prediction of the next year’s Atlantic hurricane activity are given in Table 1. Substitution of the forecast predictors in Table 1 into Equation 1 yields the forecast for the amount of next year’s Atlantic basin seasonal hurricane activity shown in Table 2. This forecast indicates somewhat below average hurricane activity during 1996. Table 2 also gives the hindcast skill associated with each prediction.

Table 1: Values of the five (input) parameters for 1995 forecast.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( U_{50} )</td>
<td>- 20 ms-l</td>
</tr>
<tr>
<td>( U_{30} )</td>
<td>- 24 ms-l</td>
</tr>
<tr>
<td>(</td>
<td>U_{50} - U_{30}</td>
</tr>
<tr>
<td>Sahel (R)</td>
<td>- 0.35 S.D.</td>
</tr>
<tr>
<td>Gulf of Guinea (R_G)</td>
<td>+0.14 S.D.</td>
</tr>
</tbody>
</table>

New and Improved Extended Range Forecast Scheme

A new version of our extended range forecasting scheme differs from the original scheme in that it involves a pool of predictors on which we employ a leaps and bounds regression method which successively chooses the best two predictors, the best three predictors, etc. up to ten predictors. Variance explained typical increases as we add predictors but at an ever decreasing rate of improvement. Given the limited pool of hindcast years (46) from which to develop our scheme, degradation occurs when the scheme is applied to independent data if too many predictors are used (i.e., over curve-fitting). Consequently, we
optimize the number of predictors, in this case we limit the number of 1996 predictors to six.

Table 2: Statistical prediction for the 1996 season as obtained with Equation 1 and the final amount of undegraded variance explained in the 41-year hindcast developmental data set.

<table>
<thead>
<tr>
<th>Forecast Parameter</th>
<th>1992 Statistical Forecast</th>
<th>Amount of Undegraded Variance Explained</th>
</tr>
</thead>
<tbody>
<tr>
<td>Named Storms (NS)</td>
<td>7.8</td>
<td>.44</td>
</tr>
<tr>
<td>Named Storm Days (NSD)</td>
<td>30.7</td>
<td>.51</td>
</tr>
<tr>
<td>Hurricanes (H)</td>
<td>6.2</td>
<td>.45</td>
</tr>
<tr>
<td>Hurricane Days (HD)</td>
<td>17.5</td>
<td>.49</td>
</tr>
<tr>
<td>Intense Hurricanes (IH)</td>
<td>2.0</td>
<td>.50</td>
</tr>
<tr>
<td>Intense Hurricane Days (IHD)</td>
<td>6.4</td>
<td>.45</td>
</tr>
<tr>
<td>Hurricane Destruction Potential (HDP)</td>
<td>52.6</td>
<td>.45</td>
</tr>
<tr>
<td>Net Tropical Cyclone activity (NTC)</td>
<td>88.7</td>
<td>.53</td>
</tr>
</tbody>
</table>

Table 3 shows the pool of ten potential predictors, their numerical value for this year's forecast and the six predictors which are chosen for each forecast of our nine forecast hurricane

Table 3: Predictor values for 1996 forecast.

<table>
<thead>
<tr>
<th>Predictor</th>
<th>Predictor Values for 1996 Forecast</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$U_{20}$</td>
</tr>
<tr>
<td>2</td>
<td>$U_{24}$</td>
</tr>
<tr>
<td>3</td>
<td>$U_{12}$</td>
</tr>
<tr>
<td>4</td>
<td>(Quito Rain (Aug-Nov)) + 0.14 S.D.</td>
</tr>
<tr>
<td>5</td>
<td>(Sahel Rainfall 4-year average) - 0.62 S.D.</td>
</tr>
<tr>
<td>6</td>
<td>Atlantic Ridge</td>
</tr>
<tr>
<td>7</td>
<td>Singapore 100 hPa TA (Jul-Nov) - 0.6 x 10^{-3}</td>
</tr>
<tr>
<td>8</td>
<td>Nino-3 (Prior 27 months) + 17.4 x 10^{-3}</td>
</tr>
<tr>
<td>9</td>
<td>Darwin SLPA (May-Jul) + 4.3 x 10^{-1} hPa</td>
</tr>
<tr>
<td>10</td>
<td>Calcutta SLPA (Aug-Nov) - 0.2 hPa</td>
</tr>
</tbody>
</table>

Top six predictors chosen for each forecast variable

<table>
<thead>
<tr>
<th>Predictors</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>NS</td>
<td>1</td>
<td>2</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NSD</td>
<td>2</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>H</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>6</td>
<td>9</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HD</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>9</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IH</td>
<td>1</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>9</td>
<td>10</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IHD</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>9</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HDP</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>8</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NTC</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>8</td>
<td>9</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MPD</td>
<td>1</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>10</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4: 1996 tropical cyclone activity prediction using our new extended range forecast scheme and with the amount of undegraded variance explained in the 46-year hindcast developmental data set.

<table>
<thead>
<tr>
<th>Forecast Parameter</th>
<th>1996 Statistical Forecast</th>
<th>Amount of Undegraded Variance Explained</th>
</tr>
</thead>
<tbody>
<tr>
<td>Named Storms (NS)</td>
<td>8.3</td>
<td>50.8</td>
</tr>
<tr>
<td>Named Storm Days (NSD)</td>
<td>39.5</td>
<td>55.2</td>
</tr>
<tr>
<td>Hurricanes (H)</td>
<td>5.4</td>
<td>48.3</td>
</tr>
<tr>
<td>Hurricane Days (HD)</td>
<td>21.2</td>
<td>54.6</td>
</tr>
<tr>
<td>Intense Hurricanes (IH)</td>
<td>2.1</td>
<td>56.1</td>
</tr>
<tr>
<td>Intense Hurricane Days (IHD)</td>
<td>6.2</td>
<td>46.9</td>
</tr>
<tr>
<td>Hurricane Destruction Potential (HDP)</td>
<td>42.0</td>
<td>50.8</td>
</tr>
<tr>
<td>Net Tropical Cyclone activity (NTC)</td>
<td>85.2</td>
<td>55.9</td>
</tr>
<tr>
<td>Maximum Potential Destruction (MPD)</td>
<td>59.3</td>
<td>62.5</td>
</tr>
</tbody>
</table>

Real forecast skill. Application of these forecast schemes to future independent data will occasion a forecast skill degradation such that the amount of variance explained will decrease by 10-25 percent. We estimate that our newer 1 December
extended range real forecast skill to range between about 35-45 percent. We consider this a skillful forecast, particularly in consideration of the extended range nature of the forecast.

Table 5 provides a comparison of both of these hurricane prediction schemes, our qualitative adjustment and the actual 1996 seasonal forecast. The 1996 forecast hurricane activity expressed as percent of the average season activity is given on the right column. Net tropical cyclone activity is expected to be about 85 percent of the average of the last 45 seasons. Though the overall activity is expected to be below average is important to note that the intense hurricane activity next year would be greater than in most years in the last couple of decades.

**ATLANTIC BASIN HURRICANE ACTIVITY IN YEARS FOLLOWING EXTREMELY ACTIVE SEASONS**

There have been ten previous hurricane seasons (1887, 1893, 1906, 1916, 1926, 1933, 1950, 1955, 1961, 1969) with activity comparable to 1995. In attempting to assess how active the 1996 season may be, it is instructive to note the level of activity during hurricane seasons following these other ten unusually active hurricane seasons. The years following unusually active seasons tend to experience somewhat below average hurricane activity. Table 6 provides a comparison of seasonal averages during the ten most active hurricane seasons (top line) versus average activity in the subsequent ten seasons (1888, 1894, 1907, 1917, 1927, 1934, 1951, 1956, 1962 and 1970) following usually active years. Also listed is the ratio of activity during the active years to that in the subsequent years. Some striking features are to be noted include the following:

1. Years following unusually active hurricane seasons tend to be suppressed in hurricane activity, particularly for intense hurricane activity.

2. Tropical cyclone activity during unusually active seasons is typically 2 to 4 times higher during the subsequent seasons, depending on the specific index of activity considered. The seasonal number of intense hurricane days, is nearly 6.5 times greater during active seasons than in following years. The net tropical cyclone activity (or NTC) is three times greater.

3. Only two of the ten "subsequent" seasons (1894 and 1951) had a total of more than five hurricanes in the subsequent season.

**Table 6: Average seasonal totals of named storms (NS), named storm days (NSD), Hurricanes (H), Hurricane Days (HD), Intense Hurricanes (IH), Intense Hurricane Days (IHD), Hurricane Destruction Potential (HDP), and Net Tropical Cyclone (NTC) activity during the ten previous most active hurricane seasons during the last 125 years (top line) versus the same average seasonal totals during the ten subsequent seasons (line 2). The ratio of active year to subsequent year activity is on the third line.**

<table>
<thead>
<tr>
<th>NS</th>
<th>NSD</th>
<th>H</th>
<th>HD</th>
<th>IH</th>
<th>IHD</th>
<th>HDP</th>
<th>NTC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ave. of Ten</td>
<td>13.9</td>
<td>95</td>
<td>9.5</td>
<td>52</td>
<td>4.7</td>
<td>14.2</td>
<td>166</td>
</tr>
<tr>
<td>Most Active Seasons</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ave. of Ten Years</td>
<td>7.3</td>
<td>38</td>
<td>4.2</td>
<td>17</td>
<td>1.2</td>
<td>2.2</td>
<td>49</td>
</tr>
<tr>
<td>Following Ten Most Active Seasons</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Active Seasons Ratio: Active Year</td>
<td>1.9</td>
<td>2.5</td>
<td>2.3</td>
<td>3.0</td>
<td>3.9</td>
<td>6.4</td>
<td>3.4</td>
</tr>
</tbody>
</table>

This trend suggests that the 1996 hurricane season will likely be a great deal less active than has been the 1995 season.

It is observed that the year preceding an unusually active hurricane season also has below average activity. For example, the average number of NS, H and IH during ten years before unusually active hurricane seasons was 7.3, 4.2, and 1.4, below the last 45-year average values of 9.3, 5.7 and 2.1. Such weak prior season activity was dramatically illustrated in 1994, one of the most inactive seasons during this century.

This alternating active-inactive tendency for seasonal hurricane activity is not a complete mystery but appears to be associated with the strong biennial nature of the atmosphere and ocean variability. The stratospheric Quasi-biennial Oscillation (QBO) is well known and the strong tendency for the troposphere to have a biennial oscillation has also been well established in observational and modeling studies. ENSO has a significant biennial mode, as do most other tropospheric phenomena including tropical cyclones.
DISCUSSION

This extended range seasonal hurricane forecast is based on the premise that the atmosphere will behave in 1996 as it has in the past; that those global environmental conditions which proceed active or inactive hurricane seasons of the past give meaningful information on the future. This hurricane forecast has also benefited from our separate and independent 1996 forecasts of ENSO conditions and of African Sahel rainfall. The atmosphere operates as a single entity and hence, each separate forecast aids our physical interpretation of the complete atmosphere-ocean-land system and in the making of other forecasts.

SCHEDULE OF ATLANTIC BASIN SEASONAL HURRICANE FORECASTS FOR 1996

This seasonal forecast for the 1996 hurricane season issued on 30 November 1995 will be updated on 5 April 1996, 6 June 1996 and 7 August 1996. A 1996 seasonal verification and a forecast for 1997 hurricane activity will be issued in late November 1996. In addition, seasonal forecasts of late summer and fall 1997 ENSO conditions, the anticipated 1997 Sahel rainfall conditions will also be issued in late November, 1996.

CAUTIONARY NOTE

It is important that the reader appreciate that these seasonal forecasts are based on statistical schemes which will fail in some years. These forecasts also do not specifically predict where within the Atlantic basin storms will strike. Even if 1996 should prove to be a somewhat average hurricane season, there are no assurances that many hurricanes will strike along the US or Caribbean Basin coastline and do much damage.

LIKELY INCREASE OF LANDFALLING MAJOR HURRICANES IN COMING DECADES

There has been a great lull in the incidence of intense category 3-4-5 hurricanes striking the US East Coast, Florida and Caribbean Basin during the last 25 years. We see this trend as a natural consequence of the slowdown in the Atlantic Ocean (thermohaline) Conveyor Belt circulation which appears to be responsible for a long list of concurrent global circulation and rainfall pattern changes (see Gray and Sheaffer, 1996). These include the Sahel drought, increased El Nino activity, Pacific and Atlantic middle latitude zonal wind increases among numerous others.

Both actual historical observations and geological (proxy) records indicate that this lull in major hurricane activity will not continue indefinitely. A return of increased major landfalling hurricane activity should be expected within the next decade or two. When this happens, the upshot of large coastal development during the last 25-30 years will very likely include hurricane destruction as never before experienced. More research on the causes and the likely timing of this change-over to increased intense hurricane activity is desperately needed. Increased intense hurricane activity striking US coastal areas is a more assured and immediate threat to the US than that of greenhouse gas warming and other environmental problems which are receiving comparatively much greater attention.

Changes in the North Atlantic. We may be seeing the early stages of the beginning speed-up of the Atlantic thermohaline (Conveyor Belt) circulation from its three decades long slow down. Aagaard (1995) has recently reported on a large decrease in ice flow through the Fram Strait (the North Atlantic passage between Greenland and Spitzbergen). This decreased ice flow reduces the introduction of fresh water and, thereby, increases surface salinity values in the North Atlantic. Recent observations report surface water salinity increases in the deep water formation areas of the North Atlantic during the last few years. Increased salinity greatly increases water density. Chilling of high salinity surface water then creates very dense water which is able to sink to great depth, thereby engendering a northward flow of warm replacement water; hence - the Atlantic conveyor.

Recent deep water observations in the North Atlantic reveal fairly stagnant water a decade or more old. The surface salinity increases that are now being measured in the North Atlantic will likely result in a speed-up of the Atlantic Ocean thermohaline circulation in the next few years. If this does occur, then we anticipate a general increase in West African Sahel rainfall, a decrease in Atlantic summertime upper tropospheric westerly winds and, regarding the issue at hand, a decade long increase of Atlantic basin intense hurricane activity. These new regional North Atlantic measurements may thereby be an ominous sign of future increases in US and Caribbean basin landfalling hurricane activity. Regardless, the quarter century lull which we have enjoyed cannot be expected to continue indefinitely into the future.

ACKNOWLEDGEMENTS

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Atmospheric and Oceanic Administration (NOAA) National Weather Service and Climate Prediction Center. The authors are indebted to a number of meteorological experts who have furnished us with the data necessary to make this forecast or who have given us valuable assessments of the current state of global atmospheric and oceanic conditions. We are particularly grateful to John Knaff and John Sheaffer for very valuable climate discussion and input data. We are grateful to Colin McAdie who has furnished much data necessary to make this forecast and to Vern Kousky, Jerry Bell, James Angell and Richard Larson for helpful discussion. The authors have also profited from indepth interchange with his project colleagues Ray Zehr, Patrick Fitzpatrick and James Kossin. William Thorson and Richard Taft have provided valuable data development and computer assistance. We wish to thank Tom Ross of NCDC, Wassila Thiaw and Vadamani Kumar of the African Desk of CPC who provided us with West African and other meteorological information. Douglas LeCompte of USDA has provided us with continuous African rainfall summaries. Barbara Brumit and Amie Hedstrom have provided manuscript and data reduction assistance. We appreciate receiving the UK Meteorological Office experimental forecasts of this summer's Sahel precipitation. We have profited over the years from many indepth discussions with most of the current NHC hurricane forecasters. These include Lixion Avila, Miles Lawrence, Max Mayfield, Richard Pasch and Edward Rappaport. The first author would further like to acknowledge the encouragement he has received over recent years for this type of forecasting research applications from Neil Frank and Robert Sheets, the former directors of the National Hurricane Center (NHC) and from Jerry Jarrell, Deputy NHC director. We look forward to a beneficial association with the new director, Robert Burpee.

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Climatological information employed in the compilation of this section is derived from published weather data of the Royal Observatory, Hong Kong and is used with the prior permission of the Director.

Review of spring 1995

Important climatological events

Although spring 1995 was not remarkable in that temperatures in all three months were generally near normal, it was unusual in being exceptionally dry. As in 1994, March posted mean daily temperatures slightly below average, this time by 0.6°C. Both April and May, in contrast, recorded mean daily temperatures of 22.5°C and 26.0°C, 0.3°C and 0.1°C respectively above the 1961-90 normal values. All three months were, however, considerably drier (48, 47 and 7 percent for March, April and May) than normal. In the latter case, May, the weather could be described as exceedingly dry without any exaggeration. The precipitation total for the season was only 129.5 mm giving a shortfall of 415.6 mm compared to the 1961-90 normal value of 545.1 mm. The lower temperatures in March may be attributed to higher amounts of cloud (79 percent or 3 percent higher than normal) and the lower amount of mean daily global solar radiation reaching the surface (9.72 MJ m⁻² or 1.52 MJ m⁻² less than normal). The drier conditions may be linked to the persistence of northeast monsoon flows as in 1994. Although April also recorded 3 percent higher mean cloud amount for the month (79 percent or 3 percent higher than normal) it was slightly warmer on the average. In the case of April, however, the mean daily global solar radiation was 0.35 MJ m⁻² above normal at 13.49 MJ m⁻², primarily as the result of an extended period of fine, sunny weather near the end of the month which was associated the dominance of an easterly airstream. Although also much drier than normal there was one heavy rain event associated with an active trough on 19th which produced more than half of the month's total and resulted in the issuance of a Flood Warning for the first time in 1995. Overall, May recorded near average temperatures although there was also a period of hot weather towards the end of the month which saw the fourth highest daily maximum temperature on record for May (34.2°C) being set on 30th. However, May was most remarkable for its dryness with only 20.8 mm or 7 percent of normal being recorded making it the second driest May since records began in 1884. Again, almost half (10.3 mm) of the monthly total fell in a single day, the 4th, in association with an active trough of low pressure. The dryness of the month as a whole may be attributed to the relative absence of active troughs which are often common in May.

Mean daily temperature 22.1°C (0.1°C)
Rainfall (provisional) 129.5 mm (24 %)

March

March was a dry month in terms of rainfall with the monthly total of 32.4 mm being only 48 percent of the March 30-year normal. It was also somewhat cooler than average with a mean air temperature of 17.9°C, 0.6°C below normal. The lower temperatures were mainly due to increased cloudiness (79 percent or 3 percent above normal) and the associated reduction in sunshine and solar radiation reaching the surface. Total bright
sunshine for the month was 80.5 hours, 15.9 hours below normal and mean daily global solar radiation was 9.72 MJ m\(^{-2}\), 86 percent of normal.

March began cloudy and cool with rain due to the influence of a moist easterly airstream. Rain fell again the next day but skies began to clear on 3rd as a dry northerly airflow reached the South China coast. The fine and dry weather continued the following day with strong winds in the early morning. The weather gradually became milder and more humid from 5th to 10th with the subsidence of the continental airstream during that period. Another surge of cool, moist northeast monsoon arrived in the territory on the night of 10th. This resulted in the prevalence of cool, humid conditions until 15th. Moderation of the monsoon led to widespread sea fog occurring on 16th with visibility dropping below 1000 m in Victoria Harbour that morning. Foggy conditions persisted the next morning but dispersed with the arrival of a cool northerly airflow that afternoon. Temperatures also dropped rapidly, reaching the minimum for the month of 12.5°C in the early morning of 18th. Cloudy conditions prevailed on 19th but the weather gradually turned fine over the next two days as winds became light. This brought thick fog again in the morning although the afternoons were generally fine. General cloudiness returned on 23rd but, apart from some morning fog, the next day was fine and warm with that sunny afternoon recording the month’s highest temperature of 25.2°C. A cold front advanced south and reach the coast during the morning of 25th giving strong, gusty winds and squally showers offshore. The strong, cool monsoon also lowered temperatures by about 4°C in a two hour period at the Royal Observatory. Rain stopped quickly that afternoon and generally fine and dry conditions prevailed for the next two days. Cloud returned from 28th to 30th with mist reported over the territory during most of the day on 29th. The month ended with occasional rain brought by a cool northeast monsoon flow.

Mean daily temperature 17.9°C (-0.6°C)
Rainfall (provisional) 32.4 mm (48 %)

April

April, like the three months before, was also a drier than normal month, with 53 percent below average rainfall of 299.8 mm being recorded. On
the whole month was slightly warmer than normal with a mean air temperature of 22.5°C. In contrast to March the month was sunnier than normal with a monthly total of 142.9 hours or 34 hours above the mean. This was mainly due to the extended period of fine weather associated with an easterly airstream towards the end of the month. Heavy rain, amounting to 42.6 mm at the Royal Observatory, associated with an active trough on the evening of 19th resulted in the issuance of the flood warning for the first time in 1995.

Under the influence of the northeast monsoon that arrived at the end of March, April began with cloudy, cool conditions with rain on the first two days of the month. Winds strengthened on 3rd and periods of rain continued as temperatures dropped to the minimum recorded for the month of 14.5 °C early that morning. The weather remained overcast for the next two days although there was no rain. Winds became light on 6th and the weather turned humid with mist and patchy rainfall that day and the next. Apart from some morning fog it was warm with sunny periods on 8th to 10th. Poor visibility in the mornings returned on 11th and it was generally cloudy with morning mist for the next couple of days. The arrival of a warm southerly airstream on 14th resulted in daily minimum temperatures recorded that morning being 5°C higher than recorded the previous day. Warm weather with long periods of sunshine characterized conditions from 15th to 18th under the influence of this airstream. On the evening of 19th a very active trough of low pressure crossed the coast bringing heavy, thundery and squally showers and the accompanying flooding. Over 60 mm of rain fell in the northeast New Territories between 6 pm and 7 pm HKT that day. Hail was also reported in Tai Po. The next day an easterly airstream brought cooler weather, but temperatures gradually rose over the next three days reaching the month's maximum of 30.2°C on the hot, sunny afternoon of 30th. The sun returned on 14th and warm weather persisted from 24th until the end of the month.

**May**

May was the fifth consecutive month of 1995 with below average rainfall. In fact it was a very dry month, with a total of only 20.8 mm or 7 percent of normal, making it the second driest May on record. Half of the monthly total fell on one day, 4th, resulting in the second issuance of a Flood Warning for 1995. The relative absence of active troughs of low pressure bringing unstable conditions and disturbed weather to the south China coastal areas was probably the most significant factor influencing the low rainfall recorded during the month. Only one other trough crossed the coast, on 21st, and it weakened rapidly and produced little rain. Although temperatures, overall, were close to normal, a period of hot weather under the influence of a maritime airstream, prevailed during the last few days of the month. The maximum temperature of 34.2°C, recorded on 30th, was the fourth highest on record.

The month began fine and hot under the influence of a southerly airstream. On 3rd a trough of low pressure developed over south China and as it approached the coast on 4th, the weather became unsettled with widespread rain and thunderstorms that afternoon. Although less than 20 mm of rain were recorded in urban areas more that 40 mm fell over the northeast New Territories. A fresh, relatively cool northeasterly airstream brought cloudy weather the next day with temperatures dropping to the month's lowest; of 20.8°C early that morning. The weather turned fine on 6th as winds moderated although this was short-lived as it became cloudy with some rain patches over the next three days. Temperatures rose rapidly again on 10th as the weather cleared up when the winds turned to the southeast. Early the next day a fresh easterly airflow reached the south China coast and the weather became cloudy with some rain patches that day and 12th. More rain fell on 13th with over 30 mm recorded in the northern New Territories. The sun returned on 14th and warm weather continued the next day until the arrival of a continental airstream bringing cooler and cloudier conditions on 16th and 17th. The clouds persisted over the next three days although temperatures gradually rose during this time. A trough of low pressure crossed the Guangdong coast during the night of 21st weakening rapidly as it reached Hong Kong. Although only traces of rain were recorded in most of the territory thundery showers brought more than 20 mm to Lantau Island. Over the next three days the weather remained cloudy and slightly cooler with light rain patches. The influence of a maritime airflow brought fine sunny conditions with some isolated showers from 25th to the end of the month. The month's highest temperature of 34.2°C was recorded on the very hot, sunny afternoon of 30th.

**Mean daily temperature 22.5°C (+0.3°C)**

**Rainfall (provisional) 76.3 mm (47 %)**

**Mean daily temperature 26.0°C (+0.1°C)**

**Rainfall (provisional) 20.8 mm (7 %)**
Review of summer 1995

Important climatological events

In sharp contrast to the relatively drier than average spring, the summer of 1995 was much wetter and somewhat cooler than usual. However, the change to a wetter than regular summer precipitation regime did not take place until July. The month of June was unusually warm and dry. The monthly mean daily minimum temperature of 27.1°C set a new record as the highest for June and the monthly mean daily temperature at 28.7°C was the third highest since records began at the Royal Observatory in 1884. Total rainfall of 243.9 mm was 132.1 mm below the 1961-90 normal amount of 376 mm making it the sixth consecutive month in 1995 with below average rainfall. Despite the relative dryness there were two heavy rain events on 14th and 18th, both associated with the passage of active troughs, which together accounted for nearly half of the month's total rainfall. In contrast, the monthly total amount of precipitation for July, 668.7 mm, was more than twice the average, making it the seventh wettest July on record. Seven days recorded more than 50 mm of rain and active southwest monsoon and low pressure troughs were largely responsible for rain falling three days out of four. The month was also duller (total bright sunshine 52.1 hours or 23 percent below normal) and cloudier (mean cloud amount 72 percent or 7 percent above normal) leading to a mean monthly daily temperature of 28.0°C, 0.8°C below normal. A very wet July preceded an extremely wet August in which the recorded monthly total rainfall of 1090.1 mm set a new record for the month and was the third highest for any month on record. The weather during the first three days of the month was mainly influenced by a broad ridge of high pressure resulting in fine, hot days with only brief showers. This sunny weather persisted the next day with the month's highest maximum temperature of 33.6°C being recorded on the afternoon of 4th. Cloudier weather then set in with heavily localized showers occurring on 5th. A fresh easterly airstream and rainy weather reached the south China coast the next day bringing rainy weather for the next two days. This was followed by an active trough of low pressure which developed over the coastal area of Guangdong on 8th and which brought heavy showers until 11th. As this trough moved southwards into the northern part of the South China Sea the weather improved giving sunny spells on 12th. However, because of the relatively cool northeasterly flow behind the trough, temperatures dropped to the month's lowest recorded minimum of 24.8°C that morning. The weather remained fine the following day but became unsettled again on 14th as the trough over the northern part of the South China Sea again moved northwards towards the coast of Guangdong. Widespread heavy and thundery showers affected the territory in the evening with over 100 mm being recorded in parts of Hong
Kong Island and in the Taipo area. This event resulted in the issuing of the Rainstorm Red Warning for the first time in 1995 and fifty-seven reports of flooding being received. The rain eased off over the following two days before another active trough of low pressure over Guangdong advanced south towards the coast on 17th. Disturbed weather again affected Hong Kong and there was widespread torrential rain and thunderstorms in the morning of 18th resulting in the Rainstorm Red Warning being issued that morning for the second time in the month. The rain was particularly heavy between 0700 and 0800 HKT. More than 100 mm fell over the urban areas during a four hour period. Altogether forty-four reports of flooding were received during the storms. Following the heavy rain a mainly fine spell of weather dominated the period from 19th to 27th. Only isolated showers occurred in an otherwise fine and hot period under the influence of a southwesterly airstream. Another trough approached the coast on 28th but this trough weakened rapidly and brought only scattered showers to the territory before the weather turned fine and hot again until the end of the month.

Mean daily temperature 28.7°C (+0.9°C)  
Rainfall (provisional) 243.9 mm (65 %)

July

July marked a turning point in the rainfall regime of Hong Kong in 1995 with above average rainfall being recorded for the first time in the year although the total accumulated rainfall at the end of the month was still 17 percent below the average for the first seven months. In fact the month was very wet, with the total rainfall of 668.7 mm being more than twice the normal, making it the seventh wettest July since records began. The month was characterized by unsettled conditions with low pressure troughs and active southwest monsoon conditions almost every day. In total seven days recorded over 50 mm of rain. The approach of Severe Tropical Storm Gary also resulted in the hoisting of tropical cyclone warning signals for the first time in 1995.

The month began mainly fine apart from some brief showers. However, an active southwest
The weather from 4th to 5th was dominated by the extension of a ridge of high pressure westwards from the Pacific Ocean towards the south China coast. This produced lengthy periods of sunshine interspersed with isolated showers. These showers became more frequent as the ridge retreated on 9th. The next two days were generally fine and hot before an unstable maritime airstream brought widespread rain and thunderstorms to the coastal areas of Guangdong on 12th. Locally, heavy morning showers were followed by torrential rain in the evening. More than 150 mm was recorded at both Shatin and Taipo on that day. Torrential rain and thunderstorms continued to affect the territory until 15th causing numerous landslips and much flooding. A total of 16 landslips occurred and 75 flood reports were made during this period. The month’s minimum temperature of 23.5°C was recorded during a heavy downpour on 15th. Isolated thundery showers continued on 16th but as a ridge of high pressure became established over south China the weather turned fine and hot from 17th to 23rd. It was during this spell of fine weather on a sunny afternoon on 22nd that the temperature reached the highest for the month, 33.4°C. Showery conditions returned on 24th and with another trough of low pressure over the coast of Guangdong, disturbed weather came back and once again thunderstorms affected the territory, this time for three days. Meanwhile Tropical Depression Gary developed over the Philippines and entered the South China Sea on 28th and the Tropical Cyclone Stand By Signal Number 1 was hoisted in Hong Kong that afternoon. The weather in Hong Kong was fine but hazy that day as Gary intensified and approached the south China coast. During the next three days Gary and its associated rainbands brought cloudy weather and more than 20 mm of rain to the territory as it moved steadily northward to make landfall near Shantou on 31st. The outer rainbands of Gary brought squally thunderstorms on the evening of that day but no significant damage was reported during the time the storm affected Hong Kong.

**Mean daily temperature** 28.0°C (-0.8°C)

**Rainfall (provisional)** 668.7 mm (207 %)

**August**

Following a very wet July the month of August can only be described as extremely wet. During the month the total amount of rainfall recorded at the Royal Observatory was 1090.1 mm the highest ever recorded for August and the third highest monthly total since records began in 1884. The monthly total was around 280 percent of the August normal of 391.4 mm. There were seven days with rainfall over 50 mm. Torrential rain fell in the period from 12th to 14th when a total of 448.3 mm was recorded at the Royal Observatory. As a result of the heavy rain the accumulated rainfall for the first eight months of 1995 amounted to 2186.4 mm, exceeding the normal for the same period by 28 percent. The rain was mainly brought about by active southwesterlies in the wake of Severe Tropical Storm Gary which made landfall near Shantou at the end of July, and by the passage of three tropical cyclones, Severe Tropical Storm Helen, Severe Tropical Storm Lois and Typhoon Kent, during the month. August 1995 was also the first August since 1946 when the Number 8 Gale or Storm signal had to be hoisted twice within the month. It was also unusually cloudy during the month with total bright sunshine averaging only 4.5 hours per day.

The first two days of August were cloudy with heavy showers as a result of the unstable southwesterly flow in the wake of Severe Tropical Storm Gary which made landfall to the west of the territory on the last day of July. As this airstream continued to affect Hong Kong there was torrential rain as thunderstorms brought between 150 and 300 mm to most parts of the territory. More than 30 reports of flooding and 17 reports of landslips were received. The weather remained unsettled with heavy thundery showers until 7th when the rain eased off. As a ridge of high pressure established itself over the south China coast conditions became generally fine from 8th to 10th. During this time Tropical Storm Helen which had formed to the east of the Philippines on 8th passed through the Balintang Channel and entered the South China Sea on 9th. The Tropical Cyclone Stand By Signal Number 1 was hoisted in Hong Kong on the afternoon of that day. Apart from some showers the weather remained fine at this time. Helen turned northwards on 10th while south of Dongsha and continued to intensify, reaching Severe Tropical Storm strength on 11th when about 400km south-southeast of Hong Kong. As Helen approached the territory the Strong Wind Signal Number 3 was hoisted early in the morning of that day. Northeasterly winds began to
strengthen and showers became more frequent resulting in the hoisting of the Gale or Storm Signal Number 8 that evening when Helen was about 140 km to the south-southeast. Stormy weather set in on the evening of 11th with gale force winds and torrential rain battering the territory as Helen passed. The storm was closest at around 0700 HKT on 12th when it was about 50 km to the east. A daily total rainfall of 242.4 mm was recorded at the Royal Observatory on that day. The Gale or Storm Signal Number 8 was replaced by the Strong Wind Signal Number 3 in the early afternoon and all signals were lowered a few hours later as Helen weakened after making landfall in the morning. Although the storm made landfall in the morning of 12th its fury still affected the coastal areas the following day. Locally, around 60 landslips were reported as a result of the heavy rain which continued to affect the territory that day and on 14th with temperatures falling to the month’s minimum of 23.1°C during a heavy rainstorm that afternoon.

The weather began to improve on 15th as a ridge of high pressure extended westwards over the south China coastal areas. The influence of this ridge resulted in a generally fine spell of weather until 23rd when its impact weakened. During this time an area of low pressure over the South China Sea developed into a tropical depression named Irving early on 18th. Moving north Irving quickly intensified and the Tropical Cyclone Stand By Signal Number 1 was hoisted shortly after noon that day. Irving’s circulation was rather compact and during its passage local weather remained fine. As instability increased heavy showers and thunderstorms developed over Guangdong and drifted south across the territory in the afternoon of 24th. Fine and hot conditions returned on 25th with the month’s highest temperature of 33.9°C being recorded that afternoon. There were frequent showers on 26th but also some sunny periods. Meanwhile, a disturbed area in the South China Sea developed into Tropical Depression Lois, moved westwards towards Hainan and became a severe tropical storm the next day. As Lois intensified the Stand By Signal Number 1 was hoisted in Hong Kong on the afternoon of 27th. Although the storm was never closer than 500 km the extensive circulation of Severe Tropical Storm Lois brought rain and squalls to the territory that day. The Number 1 signal was lowered in the morning of 28th, the rain began to ease off in the afternoon. The weather became fine apart from brief showers the next day. Tropical Depression Kent also formed over the western North Pacific Ocean on 26th and moved north-westwards towards the Luzon Strait, attaining typhoon status on 29th. Typhoon Kent entered the South China Sea on 30th and headed west-northwestwards towards the coast of Guangdong. In Hong Kong the Stand By Signal Number 1 was hoisted at noon that day. Local weather was fine with long periods of sunshine on 30th. At the same time, Typhoon Kent was moving quickly towards the coast of Guangdong. With the storm moving steadily closer the Strong Wind Signal Number 3 was hoisted in the early hours of 31st. The morning of 31st was fine and deceptively calm but as Kent was moving steadily closer the Gale or Storm Signal Number 8 was hoisted at 1300 HKT when Kent was about 130 km to the east-northeast. That afternoon and evening Kent brought stormy weather to Hong Kong with over 100 mm of rainfall was recorded. The storm weakened rapidly after making landfall and the Number 8 Signal was replaced by the Number 3 Signal at 2100 HKT and as winds subsided further, all signals were lowered just after midnight.

Mean daily temperature 27.4°C (-1.0°C) Rainfall (provisional) 1090.1 mm(279 %)
Meeting Reviews

Dinner to Honour Patrick Sham, the Founding Chairman of the Society, on his Retirement from the Directorship of the Royal Observatory, Hong Kong

Venue: Kimberley Hotel, Tsim Sha Tsui, Kowloon
Date: 30 May, 1995

Mr. Patrick Sham, the founding Chairman of the Society, retired as Director of the Royal Observatory, Hong Kong in May 1995. The Executive Committee of the Society hosted a dinner on 30 May, 1995 in honour of his retirement. This was attended by most current and past members of the Executive Committee. To recognize his many contributions to meteorology in Hong Kong and his efforts in founding the Society, a plaque from the Society was presented to him at the dinner. He was also granted lifetime Honorary Membership of the Society, the first and to date the only person so honoured.

Special Topics Lecture Series

Venue: Royal Observatory, Kowloon
Date: 22 November, 1995
Subject: Interactions Between the Tropical Intraseasonal Oscillation and El Nino

Prof. Li Chongyin of the Institute of Atmospheric Sciences, Academia Sinica, Beijing visited Hong Kong in the 3rd week of November. He has extensive experience in a wide range of research areas in the atmospheric sciences. On this occasion he reviewed for members the results of his latest research related to El Nino, focussing in particular on the interactions between El Nino and the Tropical Intraseasonal Oscillation.

Venue: Royal Observatory, Kowloon
Date: 11 December, 1995
Subject: Analysis of a Severe Rainstorm in June 1994

Prof. Liang Biqi of the Department of Atmospheric Sciences, Zhongshan University, Guangzhou presented members with an analysis of his research on a severe rainstorm event in June 1994 and a comparison with a similar case in July 1915. Prof. Li has expertise in synoptic meteorology, tropical meteorology and the study of natural disasters. He has also conducted lengthy investigations concerning rainstorms, typhoons and the tropical circulation.

Venue: Royal Observatory, Kowloon
Date: 20 December, 1995
Subject: Synoptic-scale Organization of Cloud Properties in Midlatitude and Tropical Circulation Systems

Prof. Lau Ngay-cheung of the Geophysical Fluid Dynamics Laboratory, Princeton University, USA was in Hong Kong just prior to Christmas. He presented members with an analysis of results of his latest research work on cloud properties in both midlatitude and tropical circulation systems. This work was published in the July 1995 issue of Monthly Weather Review.
Calendar of Coming Events

This section is intended for the publication of forthcoming events organized by the Society or by other organizations with similar aims. If members wish to notify the Society of any such events they should mail or fax such information to the Editor-in-chief along with their name(s) and membership number(s).

1996

Atlanta, GA, USA, January 28 - February 2

76th American Meteorological Society Meeting.

5th American Meteorological Society Symposium on "Education".

7th American Meteorological Society Symposium on "Global Change Studies".

8th American Meteorological Society Conference on "Satellite Meteorology".

9th Joint AMS/AWMA Conference on "Applications of Air Pollution Meteorology".

12th American Meteorological Society International Conference on "Interactive Information and Processing Systems for Meteorology, Oceanography and Hydrology".

12th American Meteorological Society Conference on "Biometeorology and Aerobiology".

22nd American Meteorological Society Conference on "Agricultural and Forest Meteorology".

American Meteorological Society Symposium on "Planned and Inadvertent Weather Modification".

American Meteorological Society Symposium on "Coastal Oceanic and Atmospheric Prediction".

San Francisco, CA, USA, February 19 - 23

18th American Meteorological Society Conference on "Severe Local Storms".

San Francisco, CA, USA, February 21 - 23

13th American Meteorological Society Conference on "Probability and Statistics".

Toulouse, France, March 11 - 16

17th Session of Joint Scientific Committee for the WCRP of WMO.

New Delhi, India, March 12 - 18

23rd Session of WMO/ESCAP Panel on Tropical Cyclones.

New Delhi, India, March 18 - 20

WMO Joint Seminar on "Meteorological and Hydrological Risk Assessment".

Hong Kong, March 23

7th Hong Kong Meteorological Society Annual Meeting.

Pacific Grove, CA, USA, May 23 - 24

45th Annual Meeting of the Weather Modification Association.

Toronto, ON, Canada, May 26 - 31

CMOS 30th Annual Congress.

Moscow, Russia, May 27 - 31

8th International Symposium on "Acoustic Remote Sensing and Associated Techniques of the Atmosphere and Oceans (ISARS'96)".
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<th>Location</th>
<th>Dates</th>
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<td>Istanbul, Turkey</td>
<td>June 3 - 14</td>
<td>Habitat II - United Nations Conference on &quot;Human Settlements&quot;.</td>
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<td>Essen, Germany</td>
<td>June 10 - 14</td>
<td>International Conference on &quot;Urban Climatology&quot;.</td>
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<td>Osaka, Japan</td>
<td>June 10 - 14</td>
<td>10th International Conference on &quot;Atmospheric Electricity&quot;.</td>
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<td>Seattle, WA, USA</td>
<td>June 18 - 20</td>
<td>5th International Conference on &quot;Atmospheric Sciences and Applications to Air Quality&quot;.</td>
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<tr>
<td>Edinburgh, Scotland, UK</td>
<td>July 23 - 26</td>
<td>25th American Meteorological Society Conference on &quot;Broadcast Meteorology&quot;.</td>
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<tr>
<td>Victoria, BC, Canada</td>
<td>August 12 - 15</td>
<td>International Glaciological Society International Symposium on &quot;Representation of the Cryosphere in Climate and Hydrological Models&quot;.</td>
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<td>Clermont-Ferrand, France</td>
<td>August 12 - 16</td>
<td>4th International Cloud Modelling Workshop</td>
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<td>Zurich, Switzerland</td>
<td>August 19 - 23</td>
<td>12th International Conference on &quot;Clouds and Precipitation&quot;.</td>
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<td>Norfolk, VA, USA</td>
<td>August 19 - 23</td>
<td>15th American Meteorological Society Conference on &quot;Weather Analysis and Forecasting&quot;.</td>
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<td>11th American Meteorological Society Conference on &quot;Numerical Weather Prediction&quot;.</td>
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<td>1996 International Radiation Symposium.</td>
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<td>Ljubljana, Slovenia</td>
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<td>14th International Congress of Biometeorology.</td>
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<td>7th International Conference on &quot;Mesoscale Processes&quot;.</td>
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<td>XVIII Quadrennial Ozone Symposium</td>
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<td>Fort Lauderdale, FL, USA</td>
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<td>32nd American Water Resources Association Annual Conference and Symposium on &quot;GIS and Water Resources&quot;.</td>
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<td>11th Session of World Meteorological Organization &quot;Commission for Basic Systems&quot;.</td>
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<td>Koblenz, Germany</td>
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<td>10th Session of World Meteorological Organization &quot;Commission for Hydrology&quot;.</td>
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<td>1997</td>
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<td>Long Beach, CA, USA</td>
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<td>77th American Meteorological Society Annual Meeting.</td>
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<td>3rd American Meteorological Society Conference on &quot;Atmospheric Chemistry&quot;.</td>
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<td>6th American Meteorological Society Symposium on &quot;Education&quot;.</td>
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<td>7th American Meteorological Society Conference on &quot;Aviation Weather Systems&quot;.</td>
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<td>7th American Meteorological Society Conference on &quot;Climate Variations&quot;.</td>
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<td>8th American Meteorological Society Symposium on &quot;Global Change Studies&quot;.</td>
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9th American Meteorological Society Conference on "Atmospheric Radiation".

13th American Meteorological Society International Conference on "Interactive Information and Processing Systems for Meteorology, Oceanography and Hydrology".

American Meteorological Society Conference on "Hydrology".

American Meteorological Society Symposium on "Integrated Observing Systems".

Hong Kong March 22

8th Hong Kong Meteorological Society Annual Meeting.

Pretoria, South Africa April 7 - 11

5th International Conference on "Southern Hemisphere Meteorology".
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