Title: Investigation of the "Elevated Heat Pump" Hypothesis of the Asian Monsoon Using Satellite Observations

Article Type: Original Article

Keywords: Elevated Heat Pump Hypothesis; Indian Monsoon; heating in the Tibet Plateau

Abstract: The onset and intensity of the Asian Summer Monsoon is influenced by dynamical factors, such as the El Nino/Southern Oscillation or the Indian Ocean Dipole. Recently, it has been postulated that aerosol-induced anomalous mid-and upper-tropospheric warming above the Tibetan Plateau leads to an early onset and intensification of monsoon rainfall. This so-called "Elevated Heat Pump" effect is based on results from the NASA finite-volume general circulation model with and without radiative forcing from different types of aerosols. In particular, black carbon emissions from sources in Northern India and dust from western China, Afghanistan, Pakistan, and Southwest Asia, are the driving forces behind the anomaly. The current study takes an observational approach to detect signatures of the "Elevated Heat Pump" effect in the cloud cover and cloud type distributions as derived from Meteosat-5 data over the Asian Monsoon region, supplemented with surface temperature data from the NCEP/NCAR Reanalysis and precipitation data from the Global Precipitation Climatology Project. Cloud, convection, precipitation, and surface temperature features for the highest-aerosol year of the current decade (2004) are compared with lower-aerosol content years during the period 2000 - 2005. Temperature anomalies in the Tibetan Plateau and predicted precipitation features in China and Korea are found to be consistent with the hypothesis, but the early onset and intensification of monsoon rainfall over India are not observed. It is proposed that indirect aerosol effects or the anomalies in dynamical features during the high-aerosol year caused the disagreement between observed and hypothesized behavior.
Investigation of the “Elevated Heat Pump” Hypothesis of the Asian Monsoon Using Satellite Observations

Margaret M. Wonsick, Rachel T. Pinker, and Yingtao Ma

Department of Atmospheric and Oceanic Science
University of Maryland
College Park, MD 20742

For Submission to:

Climate Dynamics

August 2009

Corresponding Author:
R. T. Pinker
pinker@atmos.umd.edu
Phone: 301-405-5380
Abstract

The onset and intensity of the Asian Summer Monsoon is influenced by dynamical factors, such as the El Nino/Southern Oscillation or the Indian Ocean Dipole. Recently, it has been postulated that aerosol-induced anomalous mid-and upper-tropospheric warming above the Tibetan Plateau leads to an early onset and intensification of monsoon rainfall. This so-called “Elevated Heat Pump” effect is based on results from the NASA finite-volume general circulation model with and without radiative forcing from different types of aerosols. In particular, black carbon emissions from sources in Northern India and dust from western China, Afghanistan, Pakistan, and Southwest Asia, are the driving forces behind the anomaly. The current study takes an observational approach to detect signatures of the “Elevated Heat Pump” effect in the cloud cover and cloud type distributions as derived from Meteosat-5 data over the Asian Monsoon region, supplemented with surface temperature data from the NCEP/NCAR Reanalysis and precipitation data from the Global Precipitation Climatology Project. Cloud, convection, precipitation, and surface temperature features for the highest-aerosol year of the current decade (2004) are compared with lower-aerosol content years during the period 2000 - 2005. Temperature anomalies in the Tibetan Plateau and predicted precipitation features in China and Korea are found to be consistent with the hypothesis, but the early onset and intensification of monsoon rainfall over India are not observed. It is proposed that indirect aerosol effects or the anomalies in dynamical features during the high-aerosol year caused the disagreement between observed and hypothesized behavior.

Key words: Elevated Heat Pump Hypothesis; Indian Monsoon; heating in the Tibet Plateau
1 Introduction

Prediction of monsoon variability is of utmost importance for the safety and economic well-being of millions of people throughout India and Asia. Despite decades of research and improvement, climate models still fall short in accurately predicting the strength, timing and seasonal variability of the Asian monsoon. One reason for this situation is that contrary to the rest of the tropical regions, modeling the Indian monsoon region is highly sensitive to initial conditions (Sperber and Palmer 1996, Krishnamurthy and Shukla 2000; Cherchi and Navarra 2003). Other particularly troubling aspects of the models are air-sea interactions, land surface effects, cloud and precipitation processes, and sea surface temperature feedbacks in the northern Indian Ocean.

As work continues to determine what processes must be incorporated into models to improve their performance, the role of aerosols in the monsoon system is gaining attention. Increased availability of aerosol data from in situ observations and remote sensing platforms makes this a promising area of exploration. Recent studies of aerosol effects on the Asian monsoon resulted in somewhat conflicting conclusions. One characteristic of aerosols is their tendency to cause temperature decreases at the earth’s surface by reflecting incoming solar radiation—the so-called “solar dimming” effect (Stanhill and Cohen 2001; Wild et al. 2004; Pinker et al. 2005). Another characteristic is the ability of aerosols such as dust and black carbon, which are abundant in the Asian monsoon region in springtime, to produce an atmospheric heating effect by absorbing solar radiation. Results from general circulation model (GCM) simulations have shown that solar dimming from aerosols can decrease the intensity of the Asian monsoon on multi-decadal time scales by weakening the land-sea temperature gradient in the region.
(Ramanathan et al. 2005). Alternatively, aerosol-induced atmospheric heating has been linked to a strengthening of the monsoon in southern China, northern India, and the Bay of Bengal by impacting circulation patterns, vertical motions, and atmospheric stability (Menon et al. 2002; Lau et al. 2006).

The focus of this study is to use observational data to examine the “Elevated Heat Pump” (EHP) hypothesis proposed by Lau et al. (2006). The basic premise of the hypothesis is that absorbing aerosols such as black carbon from northern India and dust from the deserts of western China, Afghanistan, Pakistan, and southwest Asia stack up against the foothills of the Himalayas in the pre-monsoon season and cause anomalous upper-tropospheric warming in the Tibetan Plateau region. The aerosol transport is evident in Fig. 1, which shows the long-term mean of the general circulation near the surface in April. A relatively strong band of westerlies extends from the deserts of southwest Asia toward the Indo-Gangetic Basin (IGB) at the base of the Himalayas. A southerly wind from northeast India contributes industrial black carbon to the aerosol load in the IGB. The hypothesis proposes that warming by aerosol absorption causes the air to rise and act as an “Elevated Heat Pump”, drawing in moist air from the Indian Ocean and causing an early onset of the Indian monsoon and intensification of monsoon rainfall. The sinking motion that completes the meridional circulation shifts northward, such that the southern part of the Indian subcontinent experiences dryer-than-normal conditions in the early part of the peak-monsoon season. Observational evidence of the EHP effect presented by Lau and Kim (2006) also indicates an early drawdown of the Indian monsoon season. Impacts on rainfall extend farther than the subcontinent itself, as the heat low established over the Tibetan Plateau is balanced by an elongated surface
high pressure ridge oriented southwest to northeast from the northwestern Pacific through the northern South China Sea and southern Bay of Bengal into the central Indian Ocean. This pushes the typical Mei-yu rain belt northward and suppresses precipitation in the northern Indian Ocean, eastern China, and the western Pacific, while increasing rainfall totals in central India, the northern Arabian Sea, the northern Bay of Bengal, central China, and Korea. These conclusions were reached based on 10-year runs of the NASA finite-volume GCM with and without aerosol forcing.

The role of the Tibetan Plateau as an elevated heat source has long been recognized as one of the driving mechanisms of the Asian monsoon (Flohn 1968; Yeh 1981; Murakami 1987; Ueda and Yasunari 1998). Li and Yanai (1996) observed that the reversal of the meridional temperature gradient due to intense heating of the Tibetan Plateau in springtime coincides with the onset of the monsoon. The heating of the plateau prior to monsoon onset is mainly due to sensible heat flux in the semi-arid western part of the Plateau and latent heat flux in the more humid eastern region (Flohn 1968; Yeh and Gao 1979; Luo and Yanai 1984; He et al. 1987). Taniguchi and Koike (2007) also showed that latent heat release from convective activity is responsible for heating through the depth of the troposphere in the eastern plateau, even before the rainy season begins. The EHP hypothesis suggests that warming caused by absorbing aerosols provides another mechanism to enhance the heating of the Tibetan Plateau. The potential impact of aerosol absorbing effects is magnified in this situation since the mass of the atmosphere above the plateau is roughly half of that near sea level and any heat added warms the air more effectively than over low-level terrain (Yeh 1981). This can further strengthen the
thermally induced circulation that draws in moisture from the Indian Ocean, bringing potential for increased convection.

Preliminary validation of the hypothesis was conducted by Lau and Kim (2006). Four high-aerosol years (1980, 1985, 1988, and 1991) and four low-aerosol years (1982, 1983, 1990, and 1992) were selected for the analysis based on the Total Ozone Mapping Spectrometer (TOMS) Aerosol Index (AI) (Hsu et al. 1999). The TOMS AI is a measure of how much the observed wavelength dependence of UV radiation backscattered from aerosols differs from that due to pure molecular scattering. The data record runs from 1978 through 2006, however data collected after mid-2000 exhibit inhomogeneous degradation of the instrument’s scanner mirror and therefore are not appropriate for trend analysis. Details of the problem can be found at:


Figure 2 shows the TOMS AI values for May of each year used in the analysis of Lau and Kim (2006). Of the high-aerosol years, 1988 and 1991 have significant levels of aerosols in the IGB with an AI of 3 or more. Of the low-aerosol years, 1982 and 1983 have AI values less than 2 in the IGB. The remaining 2 years in each category are less extreme, with an average AI value between 2.25 – 2.50.

The evaluation was conducted using rainfall observations from the Global Precipitation Climatology Project (GPCP) (Huffman et al. 1997) and temperature and wind fields from the NCEP/DOE-R2 reanalysis data (Kanamitsu et al. 2002) composited separately for the high- and low-aerosol years. In agreement with the hypothesis, the following features were found in the high aerosol years: Composite rainfall data showed an increase in precipitation in northern India in the early part of the season, spreading to
all of India in June and July, and decreasing in August; enhanced ascent of warm air
along the Himalayan foothills in May was evident in the composite wind fields;
statistically significant correlation between high aerosol levels and warm upper
tropospheric temperature anomalies in northern India and the Tibetan Plateau were found.
An opposite behavior was observed during the low aerosol years.

Bollasina et al. (2008) conducted an evaluation of the EHP hypothesis using
regressions of various parameters such as precipitation, diabatic heating, winds, and
radiative fluxes on the TOMS AI for May of the years 1979-1992. In contrast to the
results of Lau and Kim (2006), they concluded that high aerosol loads in the IGB were
associated with deficient precipitation throughout India in early spring. Additionally,
their results suggest that land-surface processes set in motion by high aerosol
concentrations, rather than the EHP mechanism, led to stronger monsoon rainfall during
the months of June and July.

The approach used in the current work utilizes newly available information on
several crucial parameters for confirming the existence of the EHP effect. In contrast to
the previous studies that used TOMS AI, the springtime aerosol load in the IGB is
determined from aerosol optical depth retrieved from the Moderate Resolution Imaging
Spectroradiometer (MODIS) (Kaufman et al. 1997) and the Multiangle Imaging
Spectroradiometer (MISR) (Bothwell et al. 2002). Retrieval of information on aerosols
from TOMS is based on the backscattered radiance measurements in the range from 331
to 380 nm and provides a quantity known as the aerosol index (AI). Theoretical model
simulations (Herman, 1997; Torres, 1998) have shown that the AI depends on aerosol
optical depth (AOD), single scattering albedo, and aerosol height. It is a measure of how
much the wavelength dependence of backscattered UV radiation from an atmosphere containing aerosols differs from that of a pure molecular atmosphere. Since the underlying Rayleigh scattering in the boundary layer is small, TOMS AI is more sensitive to aerosol loading at upper levels than near the surface. Retrieval of information on aerosols from instruments like MODIS, MISR, or the Advance Very High Resolution Radiometer (AVHRR) is based on the reflected radiation and provides information on the total columnar AOD.

Cloud and convection data used in the analysis are ascertained from a recently developed dataset based on hourly Meteosat-5 satellite observations at 0.125° resolution. The high spatial resolution of this product allows a detailed investigation of cloud patterns in the Himalaya foothills region where much of the EHP effect is proposed to play out, and the high temporal resolution gives a good measure of the frequency of occurrence of convection. Finally, the monsoon behavior during individual years is analyzed in relation to the aerosol load in the IGB for each year. This approach is favored over analyzing the composite of several years because the predicted patterns should be evident during extreme aerosol years if the EHP mechanism is operating as hypothesized.

2 Data

2.1 Aerosols

The determination of springtime aerosol loading is made by analyzing aerosol retrievals from MISR and MODIS. Figure 3 shows the time series of mean AOD in the IGB for the years 2000 – 2005 for both sensors. The values are calculated by averaging the 1° x 1° resolution monthly mean AOD data over the months of March – May for the domain of 21° N – 29.5° N, 73° E – 90° E. It should be noted that the average is taken for
the months of April – May in 2000 because March values are unavailable. Based on the other years of available data, AOD in March ranges from 7% – 34% less than the values in April. Therefore, the average springtime values of AOD for 2000 most likely overestimate the actual values. Nevertheless, both data sources agree that 2004 had the highest springtime aerosol loading and that aerosol content is much lower in the years 2001 and 2005. Prasad and Singh (2007) compared MODIS and MISR AOD in the IGB to ground-based observations from the Aerosol Robotic Network (AERONET) for the years 2000-2005. They found that MISR retrievals were in closer agreement to ground observations than MODIS for both winter and summer seasons, attributable to the multi-angle viewing capabilities and the spectral resolution of the MISR instrument.

2.2 Clouds and convection

Radiance observations from Meteosat-5 at hourly resolution are used to determine cloud amount and frequency of occurrence of convection. Total cloud amounts are derived using a 2-channel cloud detection scheme modified from the Clouds from AVHRR (CLAVR) algorithm used for the Advanced Very High Resolution Radiometer instrument aboard NOAA polar orbiting satellites (Stowe et al. 1999). The basic algorithm compares 11.5 μm brightness temperature and visible reflectivity to empirically-derived cloud thresholds. The cloud detection is first performed at pixel-level (5 km) resolution, and then re-projected onto a 0.125° latitude-longitude grid. Details of the algorithm are given in Wonsick et al. (2009).

Convective cloud determination is based on Meteosat-5 11.5 μm brightness temperature and cloud optical depth as estimated by the University of Maryland Surface Radiation Budget (UMD/SRB) model (Pinker et al. 2003). The cloud optical depth
threshold for convective clouds is set to 23 as in the International Satellite Cloud Climatology Project (ISCCP) convective cloud algorithm (Rossow and Schiffer 1991), and the brightness temperature cutoff is 250 K.

The cloud screening method is limited in its ability to accurately detect clouds at night when visible data are unavailable and the algorithm relies solely on the brightness temperature observations. For this reason, cloud data are only calculated where solar zenith angle (the angle between the sun and the pixel zenith) is less than 75°. For the domain of 51° E to 136° E longitude, this roughly corresponds to the hours of 00 – 13 UTC. The lack of nighttime cloud data does not appear to hamper the analysis for several reasons. First, clouds and convection are analyzed in a relative sense of high-aerosol year versus low-aerosol year, so absolute values of cloud amount and convection have lesser importance. Second, the percentage of convection missed overnight in the areas of interest is small because convection over land peaks in late afternoon in the Indian monsoon region (Gray and Jacobson 1977; Dai et al. 2001; Islam et al. 2004.). Third, cloud patterns derived from Meteosat-5 show close agreement with rainfall amounts from other sources, indicating that they capture the situation quite well.

2.3 Temperature and rainfall

As in the study by Lau and Kim (2006), surface temperature data from the NCEP/DOE-R2 reanalysis and precipitation data from GPCP are incorporated into the hypothesis validation. Additionally, rainfall information from ground based observations from the Indian Institute of Tropical Meteorology (IITM) at Pune (Parthasarathy et al. 1995) is used. The rain gauge network consists of 306 stations, and monthly mean rainfall
amounts are computed for 30 subdivisions in India using an area-weighted average (Fig. 4).

3 Methodology

The years 2000 – 2005 are used for the study based on the overlap between availability of aerosol information from modern sensors and the Meteosat-5 satellite imagery used to derive cloud amount and convection. In light of the aerosol retrievals shown in Fig. 3, the following classifications are made: 2004 = high-aerosol year; 2001 and 2005 = low-aerosol years; 2000, 2002, and 2003 = moderate-aerosol years. The following verifiable aspects of the proposed EHP effect are assessed in relation to the aerosol load for each year: (1) the surface temperature in the Tibetan Plateau region during April should be higher in the high aerosol year due to aerosol absorption of shortwave radiation, (2) convection and precipitation in the foothills of the Himalayas and in northern India should be higher in May during the high aerosol year due to the early onset of the monsoon, (3) convection and precipitation in southern India should be lower in June in the high aerosol year due to the northward shift in the subsiding branch of the meridional circulation over India, (4) convection and precipitation for the peak-monsoon season in the high aerosol year should be higher in northern India and the Bay of Bengal, and lower in eastern Asia, the northern Indian Ocean, and the western Pacific.

4 Results

4.1 Surface temperature

According to the EHP hypothesis, in the high-aerosol year the Tibetan Plateau should undergo anomalous upper tropospheric warming in April due to absorption of shortwave radiation by aerosols. Figure 5 shows the April 400 mb temperature anomaly
from the NCEP/DOE-R2 Reanalysis for the high aerosol year. The anomaly is based on climatology from 1968-1996. Although anomalous warming is observed over the Tibetan Plateau in the high-aerosol year, the center of the anomaly is located north of 45° N and cannot be attributed to heating from aerosol absorption.

4.2 Convection and precipitation

According to the hypothesis, the anomalous warming observed over the Tibetan Plateau should accelerate the monsoon cycle and enhance convection in the foothills of the Himalayas in May during a high-aerosol year. The difference between frequency of occurrence of convection in the foothills for May 2004 and May of the other years of the study is shown in Fig. 6. Frequency of occurrence of convection is computed for each point in the domain as the number of daytime hours in the month in which cloud top temperature and optical depth meet the convective cloud criteria outlined in Section 2.2. In Fig. 6e there is evidence of an increase in convection in the high-aerosol year in comparison to 2005, the lowest aerosol year. This gives some weight to the prediction that the high aerosol load accelerates the monsoon onset. However, there is little increase in convection in comparison to the other low aerosol year (2001, Fig. 6b). In fact, the largest increase in convection occurs relative to 2003, which should be unrelated to the EHP hypothesis since it is a moderate-aerosol year.

The frequency of occurrence of convection in the Himalaya foothills region derived from Meteosat-5 agrees well with rain gauge data collected by the IITM. Table 1 shows the May rainfall totals for the years 2000 – 2005 for 7 subdivisions located in the Himalaya foothills region as shown in Fig. 4. The data confirm that 2004 precipitation
was higher than 2003 and 2005 in all subdivisions and lower than 2001 in all but the easternmost subdivision.

In addition to the proposed increase in convection in the foothills region, the simulations of Lau et al. (2006) predict enhanced precipitation in northern India (~20° N) during May of the high aerosol year. Figure 7 shows the difference in frequency of occurrence of convection for all of India between May of 2004 and the average of the months of May for the mid- and low-aerosol years. In contrast to what is expected, a significant increase in clouds and convection occurred during the high-aerosol year in southern India and the southern parts of the Arabian Sea and Bay of Bengal. The majority of the region north of 20° N experienced a decrease in convection during 2004. The similarity in patterns for the mid- and low-aerosol years seems to indicate that the aerosol loading in the IGB is not a major influence on the convective activity.

Throughout the peak monsoon season (June – September) there are some discrepancies between the behavior predicted by the EHP hypothesis and the observed convection. By June, the subsiding branch of the meridional circulation that balances the forced ascent in the foothills should be well-established, causing a decrease in convection in southern India in the high-aerosol year. This aspect of the hypothesis is evident in Fig. 8, which shows the difference in frequency of occurrence of convection between June of 2004 and the average of the months of June for the mid- and low-aerosol years. The convection patterns in southern India are reversed from May, with less convection occurring in the high-aerosol year. Note however that this pattern holds throughout the entire sub-continent, whereas the hypothesis prescribes that precipitation in the north in
2004 should still exceed that in the low-aerosol years because of the early progression of the monsoon.

Frequency of occurrence of convection for each July of 2000 – 2005 is displayed in Fig. 9. The year 2004 is second only to 2002 (an extremely notable drought year) as the year with the least amount of convection in the Indian subcontinent. The year 2001 had the highest occurrence of convection, and 2005 had a considerable amount as well. This contradicts the hypothesis, which predicts more precipitation in the high aerosol year.

As shown in Fig. 10, it is not until August that convection in northwest India and the northern Bay of Bengal in the high-aerosol year exceeds that in the low-aerosol years. This again contradicts the hypothesis, which asserts an early start to the monsoon and an early drawdown to the season.

Figure 11 shows the difference in overall rainfall patterns for the combined months of June, July, and August for the high aerosol year minus the low aerosol years. Precipitation is derived from the GPCP database. There is less precipitation throughout most of India, the northern Bay of Bengal, and southern China during the high-aerosol year. Positive rainfall differences occurred in the southern parts of the Arabian Sea and Bay of Bengal, central China, and Korea. These patterns disagree with what was predicted by the EHP hypothesis in the region of India and its surrounding waters, although they do agree over China and Korea.

5 Discussion

While it would have been interesting to perform the current analysis for the years used by Lau and Kim (2006), the sources of high-resolution cloud and aerosol
information chosen for this study were not available until 1998 and 2000, respectively. Therefore, the years 2000 – 2005 were used for the study based on the overlap between availability of aerosol information from modern sensors and the *Meteosat-5* satellite imagery used to derive clouds and convection. If the EHP hypothesis truly characterizes the impact of aerosols on monsoon behavior, its effects should be evident when comparing 2004, which had the highest aerosol load of the decade, with low aerosol years such as 2001 and 2005. While some of the behavior predicted by the EHP hypothesis was observed to occur in this study, many events unfolded contrary to what was anticipated. Several possible reasons for why the observations did not agree with the predictions are explored here.

5.1 Global influences on monsoon rainfall

The effect of aerosol forcing cannot be considered in isolation because other large-scale forcing factors affect the interannual variability of the Indian monsoon. Global teleconnections have been found between Indian Summer Monsoon Rainfall (ISMR) and various atmospheric and oceanic patterns outside the Indian monsoon region. Of the numerous indicators, some of the most prominent are El Nino/Southern Oscillation (ENSO), the North Atlantic Oscillation (NAO), and Eurasian snow cover. Analysis of the record of ISMR for the last century shows a strong correlation between drought years and the warm phase of ENSO (Kumar et al. 2006; Chakraborty and Krishnamurti 2003; Krishnamurthy and Goswami 2000, Rasmussen and Carpenter 1983). A high winter value of the NAO Index, which measures the strength of mid-latitude westerlies in the North Atlantic, has been linked to deficient monsoon rainfall the following summer (Kakade and Dugam 2006; Dugam et al. 1997). Additionally, an
inverse relationship has been observed between the amount of Eurasian snow cover and ISMR (Hahn and Shukla 1976; Parthasarathy and Yang 1995; Bamzai and Shukla 1999). These factors would not have been captured by the model simulations used to develop the EHP hypothesis, so it is possible that their influence could mask or take precedence over the EHP effect. While it is impossible to fully separate the interactions between the various forcings and responses, it is useful to examine the larger picture and investigate the influence of each of these teleconnections on monsoon behavior for the period of interest.

The interannual variability of the aforementioned factors as well as the average springtime aerosol load in the IGB is compared to the variation in monsoon conditions seen for the years 2000 – 2005. Figure 12a shows the All-India rainfall for June – August as derived from the IITM rain gauge data. The dashed line represents the average seasonal rainfall from the period 1871 – 2002. Figure 12b shows the average MISR springtime AOD values along with the Eurasian snow cover anomaly and the NAO and ENSO indices for 2000 – 2005. It is evident that high AOD values do not correspond to the increased rainfall proposed by the hypothesis, and low AOD values are not associated with decreased rainfall. The inverse relationship between Eurasian snow cover and ISMR is observed for the years 2000, 2002, and 2004. The snow cover anomaly is nearly neutral in 2001 and quite high in 2003, yet ISMR in both years is very close to average. The year 2005 does not fit the pattern as both snow cover and ISMR are lower than average. The correlations between the NAO Index and ISMR nearly mirror those of the Eurasian snow cover anomaly. The main differences are that the NAO Index is only weakly positive in 2004 when rainfall is extremely low and it is not as high as the snow cover anomaly in
2003. Recent studies have shown that the relationship between the ENSO Index and ISMR has broken down in the last two decades (Kumar et al. 1999; Chang et al. 2001). In the period of interest, the ENSO Index shows a cold phase for the years 2000 – 2002 and a warm phase for 2003 – 2005. Therefore, 2004 and 2005 are the only years that fit the classic pattern of below-average rainfall during the warm phase of ENSO. Based on these data, it appears that the patterns of monsoon rainfall for the years of this study are not strictly controlled by what is prescribed by the large-scale forcing factors.

5.2 Model inaccuracies

Disparities in predicted monsoon behavior have been seen between fixed sea surface temperature (SST) models and coupled ocean-atmosphere models. The model used by Lau et al. (2006) to develop the EHP hypothesis used fixed SSTs and predicted enhanced Asian monsoon rainfall. Similarly, the study conducted by Menon et al. (2002) with a fixed SST model also found increased monsoon precipitation in parts of India and China and decreased precipitation in the northern Indian Ocean. Alternatively, simulations with coupled models by Ramanathan et al. (2005) and Meehl et al. (2007) resulted in less Asian monsoon precipitation. When the SSTs were allowed to respond to the decreased solar radiation in northern India and surrounding waters due to aerosol absorption, the meridional SST gradient weakened. Since this gradient is one of the major driving mechanisms of the monsoon, precipitation decreased in turn.

Although climate models are valuable tools for assessing the impact of changes in individual variables, the results can be skewed by model deficiencies and biases, as well as inaccuracies in initial conditions. Observation-based studies such as the current work are complementary to model simulations and can point to parts of the model that may
need improvement. In this case, the observations support the model’s prediction of upper
tropospheric warming above the Tibetan Plateau but not the early onset, intensification,
and early drawdown of the monsoon.

5.3 Cloud microphysics

Lau et al. (2006) acknowledge that the simulations leading to the EHP hypothesis
address only direct aerosol effects (absorption and reflection of solar radiation), and that
aerosol indirect effects could complicate matters. The indirect effects of aerosols can take
several forms. In the first indirect effect (Twomey effect), aerosols act as cloud
condensation nuclei to produce more numerous cloud droplets with smaller sizes. This
implies higher cloud reflectance and cloud optical depths. The second indirect effect (also
called the cloud lifetime effect) directly follows: small cloud droplets are less efficient at
generating precipitation, resulting in longer cloud lifetimes in polluted clouds than in
cleaner clouds. Additionally, absorption of solar radiation by aerosols heats the
atmosphere and may cause evaporation of clouds—the so-called semi-direct effect.

Evidence of this behavior of aerosols has been identified in the Asian monsoon
region by numerous investigators. Heymsfield and McFarquhar (2001) analyzed aircraft
data from flights made through polluted and clean clouds in the Indian Ocean during
INDOEX (Ramanathan et al. 2001) and found a three-fold increase in droplet
concentrations and a 35% decrease in droplet effective size in polluted clouds. Their
simulations with a 1D parcel model further implied a doubling of cloud optical depth
with the high aerosol concentrations. Chylek et al. (2006) investigated the Twomey effect
over the Indian subcontinent and surrounding waters using data from MODIS (Kaufman
et al. 1997; Tanre et al. 1997). The cloud droplet effective radii retrieved from MODIS in
clean months (the average of September months of the years 2000 – 2004) were up to 33% smaller than those retrieved in polluted months (Januarys of 2000 – 2004). Largest differences occurred in the land regions north of the Bay of Bengal, corresponding to regions of peak aerosol optical depth. Ackerman et al. (2000) found that the semi-direct effect from the haze layer observed during INDOEX 1998 and 1999 was responsible for a 25% and 40% decrease in fractional cloud cover, respectively.

Bollasina et al. (2008) observed that the semi-direct aerosol effect appeared to have a strong influence on pre-monsoon precipitation in the IGB. Their regression of rainfall on the TOMS aerosol index for the years 1979-1992 showed a link between high aerosol load and deficient springtime precipitation, which they attributed to dissipation of clouds through the aerosol semi-direct effect. To determine if such a link exists in the data used in the current study, the spatial correlation between MODIS AOD and Meteosat-5 derived frequency of occurrence of convection in the Himalaya foothills region in May is calculated for each year of the study period. Results are shown in Table 2. The negative correlation is apparent for all years, albeit more strongly for some years.

In explanation of the contrast between their findings and the enhancement of precipitation in the IGB in May observed by Lau and Kim (2006), Bollasina et al. (2008) noted the different mechanisms at work in the eastern and western parts of the IGB. In the western region where the aerosol load is highest, precipitation appeared to be subdued by the aerosol semi-direct effect. Some increase in precipitation was seen in the eastern region, where the large-scale circulation flows northward over the Bay of Bengal, picking up abundant moisture and rising orographically when it encounters the Himalayas. Their results suggest that the high aerosol load in the west may affect the large-scale circulation
in a manner that enhances this precipitation-producing mechanism in the east. However, the aerosol load in the east is rather small and does not directly cause rising motion through the EHP mechanism. Furthermore, they assert that since Lau and Kim (2006) used a longitudinal average of precipitation across the IGB, the rainfall reduction in the west was masked by the activity in the east.

The details brought forth by the high-resolution Meteosat-5 data support the conclusions of Bollasina et al. (2008). Referring back to Fig. 6, it is clear that the most significant increase in convection during the high-aerosol year occurs in the eastern regions. The western part of the IGB predominantly shows decreases in convection, or slight increases interspersed with decreases. Based on these results along with the negative correlation found between AOD and frequency of occurrence of convection, it appears that the aerosol semi-direct effect plays an important role in observed behavior of the monsoon for this period of study.

5.4 Anomalies in 2004

In 2004, not only did the enhanced precipitation predicted for India under the EHP hypothesis not materialize, but it was, in fact, a notable drought year. Indian Summer Monsoon Rainfall (ISMR) lagged 13% below normal rainfall totals. Jenamani et al. (2007) found multiple factors that led to the failure of the 2004 monsoon. First, there was a decided shortfall of depressions in the region. The three depressions that formed represent less than half of the number expected on the average. Since the 1960s, the number of depressions formed during the monsoon season has been on a steady decline (Singh 2001), but in years with few depressions there is often compensation from a higher number of persistent lows (Jenamani 2004). This was not the case in 2004, when
the number of lows was near normal. It was further noted that many of the semi-
permanent systems that are highly correlated with the strength of the monsoon were in
unfavorable positions in 2004, particularly during the month of July, which had the
largest rainfall deficit. The strength of the Mascarene High, which is key to the pressure
gradient that drives the monsoon, was 1 – 2 hPa below normal. The monsoon trough lay
at the foothills of the Himalayas during much of July—too far north to produce typical
monsoon rainfall on the Indian subcontinent. The Tibetan Anticyclone which forms in the
upper troposphere due to the heating effect of the Tibetan Plateau was displaced 5°
southward of its usual position. This type of shift is known to cause break periods in the
monsoon. Finally, southwesterly onshore flow from the low level jet in the Arabian Sea
was weaker than normal, limiting the amount of moisture transported onto the
subcontinent. With all of these factors working against the development of a productive
monsoon, it is possible that the EHP effect was overwhelmed in this particular year.

6 Conclusions

The high spatial and temporal resolution of Meteosat-5 satellite data along with
improved aerosol information from sources such as MODIS and MISR provide a unique
opportunity to investigate processes that affect the Asian monsoon. This study exploits
these capabilities to apply a different approach for evaluating the EHP hypothesis. It was
found that in some aspects, observations were in agreement with the hypothesis but not in
all aspects of it.

- Anomalous warming over the Tibetan Plateau was observed but appears
too far north to be associated with the absorbing aerosols in the IGB
– Enhanced convection in the foothills of the Himalayas and increased precipitation in northern India in May was not observed

– Suppression of precipitation in southern India in June was observed

– Early drawdown of monsoon was not observed

– Overall cloud and precipitation patterns for JJA
  
  - Did not match hypothesis for India and surrounding oceans
  
  - Did match hypothesis for central China and Korea

There are several factors that may have been responsible for discrepancies between the Meteosat-5 derived cloud and convection patterns and those predicted by the EHP hypothesis:

– The impact of ocean/atmosphere coupling was not accounted for in the model simulation used to develop the EHP hypothesis.

– The model simulation did not account for aerosol semi-direct effects, which seem to be responsible for reduced precipitation in the western portion of the IGB under high aerosol load.

– Many anomalous dynamical factors combined to make 2004 a notable drought year. These factors may have masked evidence of the EHP effect.

The challenge in addressing the EHP hypothesis in an observational framework is to extract the signal of aerosol effects from other large-scale forcing factors that affect the inter-annual variability of the Asian monsoon. The model runs used to develop the hypothesis do not account for factors such as ENSO and snow cover changes, but rather focus on the aerosol effect stand alone. Lau and Kim (2006) report a detectable signal based on simulations for composite observations from 4 high aerosol years; no attempt is
made to analyze other factors that could have influenced the strength of the monsoon in those years. We have isolated single years of high and low aerosol loading using the most advanced methods of aerosol monitoring. It was found that the EHP effect was not detected in the year in which it should have been most observable. One might conclude that if the EHP mechanism does operate as proposed, its effect does not dominate other large-scale forcings and therefore, stand alone it may not be a reliable predictor of seasonal monsoon intensity. The possibility does exist that the aerosol effect can counteract or work synergistically to modify the impact of other forcing factors. A study of longer duration would be useful to better determine the relative contributions of aerosol vs. larger-scale forcing. The satellite based information developed in this study and the improved aerosol information provide the needed information to analyze the patterns of clouds and convection in the IGB. The length of the data record from MODIS and MISR is increasing and geostationary satellite coverage of the Asian monsoon region continues with the replacement of Meteosat-5 by Meteosat-7 in 2006. This is setting the stage for extending the present study for longer time periods to cover a larger number of extreme aerosol years.
Acknowledgements

This work was supported under NASA grant NNG05GB35G to the University of Maryland. The authors wish to thank Yves Govaerts and the staff at the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) Archive and Retrieval Facility for providing the Meteosat-5 observations and consulting on the calibration. Thanks are also due to the National Snow and Ice Data Center (NSIDC) at the University of Colorado, Boulder, CO, for providing the IMS snow data, the NASA/GSFC TOMS group for providing the TOMS aerosol data, and to NOAA/OAR/ESRL PSD, Boulder, Colorado, USA for providing the Reanalysis 2 data. MODIS figures were downloaded from the Goddard Earth Sciences Data and Information Services Center (GES DISC) Giovanni web site.
References


Flohn H (1968) Contributions to a meteorology of the Tibetan Highlands. Atmos Sci Paper No. 130, Colorado State University, Fort Collins CO, 120 pp


Pinker RT, Tarpley JD, Laszlo I (2003) Surface radiation budget in support of the GEWEX Continental-Scale International Project (GCIP) and the GEWEX American Prediction Project (GAPP), including the North American Land Data
Assimilation System (NLDAS) Project. J Geophys Res.

Doi:10.1029/2002JD003301


Ueda H, Yasunari T (1998) Role of warming over the Tibetan Plateau in early onset of the summer monsoon over the Bay of Bengal and the South China Sea, J Meteorol Soc Japan 76:1-12


Yeh T C, Gao YX (1979) The meteorology of the Qinghai-Xizang (Tibet) Plateau. Science Press, Beijing
List of Figures

Fig. 1  Long term mean (1968-1996) 1000 mb wind vectors for April from NCEP/NCAR Re-analysis. Colors represent wind speed in m/s.

Fig. 2  TOMS aerosol index for May of the years used in the study by Lau et al. (2006). High aerosol years are shown in top row and low aerosol years are shown in bottom row.

Fig. 3  Mean daytime aerosol optical depth at 0.55 μm in the Indo-Gangetic Basin (21° N – 29.5° N, 73° E – 90° E) averaged over the months of March – May*, as derived from a) MISR, and b) MODIS. *Average is taken for the months of April – May in 2000 because March values are unavailable.

Fig. 4  Meteorological subdivisions of India used to compile rain gauge data from the Indian Institute of Tropical Meteorology at Pune.

Fig. 5  400 mb temperature anomaly (°C) from NCEP/DOE-R2 Reanalysis for April 2004.


Fig. 7  May 2004 – average of May for the low-aerosol years, and b) May 2004 – average of Difference in frequency of occurrence of convection derived from Meteosat-5 for a) May for the mid-aerosol years.

Fig. 8  Difference in frequency of occurrence of convection derived from Meteosat-5 for a) June 2004 – average of June for the low-aerosol years, and b) June 2004 – average of June for the mid-aerosol years.
Fig. 9  Frequency of occurrence of convection derived from *Meteosat-5* for July of 2000 – 2005

Fig. 10  Difference in frequency of occurrence of convection derived from *Meteosat-5* for a) August 2004 – August 2001 and b) August 2004 – August 2005

Fig. 11  Difference in GPCP rainfall (mm/day) for a) JJA 2004 – JJA 2001, b) JJA 2004 – JJA 2005

Fig. 12  a) All India Rainfall from Jun – Aug for the years 2000 – 2005 (dashed line gives average seasonal rainfall for the period 1871 – 2002), b) Eurasian snowfall anomaly, NAO Index, and ENSO Index for the same years
Fig. 1  Long term mean (1968-1996) 1000 mb wind vectors for April from NCEP/NCAR Re-analysis. Colors represent wind speed in m/s
Fig. 2  TOMS aerosol index for May of the years used in the study by Lau et al. (2006). High aerosol years are shown in top row and low aerosol years are shown in bottom row.
Fig. 3 Mean daytime aerosol optical depth at 0.55 μm in the Indo-Gangetic Basin (21° N – 29.5° N, 73° E – 90° E) averaged over the months of March – May*, as derived from a) MISR, and b) MODIS. *Average is taken for the months of April – May in 2000 because March values are unavailable.
Fig. 4  

Meteorological subdivisions of India used to compile rain gauge data from the Indian Institute of Tropical Meteorology at Pune
Fig. 5 400 mb temperature anomaly (°C) from NCEP/DOE-R2 Reanalysis for April 2004
Fig. 7 May 2004 – average of May for the low-aerosol years, and b) May 2004 – average of Difference in frequency of occurrence of convection derived from Meteosat-5 for a) May for the mid-aerosol years
Fig. 8  Difference in frequency of occurrence of convection derived from Meteosat-5 for a) June 2004 – average of June for the low-aerosol years, and b) June 2004 – average of June for the mid-aerosol years
Fig. 9  Frequency of occurrence of convection derived from Meteosat-5 for July of 2000 – 2005
Fig. 10  Difference in frequency of occurrence of convection derived from *Meteosat-5* for a) August 2004 – August 2001 and b) August 2004 – August 2005
Fig. 11  Difference in GPCP rainfall (mm/day) for a) JJA 2004 – JJA 2001, b) JJA 2004 – JJA 2005
**Fig. 12**  
a) All India Rainfall from Jun – Aug for the years 2000 – 2005 (dashed line gives average seasonal rainfall for the period 1871 – 2002), b) Eurasian snowfall anomaly, NAO Index, ENSO Index, and average springtime (Mar – May) aerosol load in the IGB from MISR for the same years
Table 1  May rainfall totals derived from IITM rain gauge data for subdivisions in the Himalaya foothills region as shown in Fig. 4

<table>
<thead>
<tr>
<th></th>
<th>Sub 3</th>
<th>Sub 5</th>
<th>Sub 9</th>
<th>Sub 10</th>
<th>Sub 11</th>
<th>Sub 13</th>
<th>Sub 14</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
<td>3152</td>
<td>2995</td>
<td>1551</td>
<td>505</td>
<td>382</td>
<td>365</td>
<td>440</td>
</tr>
<tr>
<td>2001</td>
<td>2331</td>
<td>2933</td>
<td>1406</td>
<td>404</td>
<td>352</td>
<td>773</td>
<td>507</td>
</tr>
<tr>
<td>2002</td>
<td>2191</td>
<td>1241</td>
<td>926</td>
<td>340</td>
<td>407</td>
<td>748</td>
<td>332</td>
</tr>
<tr>
<td>2003</td>
<td>2137</td>
<td>1865</td>
<td>549</td>
<td>34</td>
<td>65</td>
<td>141</td>
<td>61</td>
</tr>
<tr>
<td>2004</td>
<td>3646</td>
<td>2285</td>
<td>830</td>
<td>231</td>
<td>347</td>
<td>537</td>
<td>484</td>
</tr>
<tr>
<td>2005</td>
<td>2872</td>
<td>1982</td>
<td>254</td>
<td>129</td>
<td>104</td>
<td>107</td>
<td>13</td>
</tr>
</tbody>
</table>
Table 2  Spatial correlation between MODIS AOD and frequency of convection
derived from *Meteosat-5* for May of 2000-2005 for the region bounded by
25° N - 33° N and 70° E - 100° E (Himalaya foothills)

<table>
<thead>
<tr>
<th></th>
<th>2000</th>
<th>2001</th>
<th>2002</th>
<th>2003</th>
<th>2004</th>
<th>2005</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>-0.58</td>
<td>-0.56</td>
<td>-0.67</td>
<td>-0.57</td>
<td>-0.57</td>
<td>-0.44</td>
</tr>
</tbody>
</table>