Closeup of the White Range near Huaraz, Ancash, Peru.

EFFECT OF GLOBAL CLIMATE CHANGE

ON THE WHITE RANGE OF PERU

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Abstract. Global climate change threatens to upset the delicate balance of Nature. The sustained warming of the past 50 years has produced a host of negative effects. In this paper we highlight the effect that global warming has had on the tropical glaciers, including melting, recession, and their possible eventual disappearance. We specifically focus on the White Range of Peru, a resource of global importance and significant natural and aesthetic value.

Global average surface temperatures have increased about 0.6°C in the past 50 years. The rise in temperatures has negatively affected the tropical glaciers, causing a decrease in total volume and aerial coverage. Glacier melting has caused an increase in the number of glacial lakes in the White Range. Continuing glacier melting poses a significant threat of recurring glacial lake outburst floods (GLOF). Relevant scientific understanding, coupled with enlightened interdisciplinary management, is necessary for the national government of Peru and its partners in the international community to develop an effective strategy to cope with these threats. Sustainability being out of the question, the aim remains to mitigate/reduce the effects of global warming within the next one to two generations.

1. GLOBAL CLIMATE CHANGE

Global climate change refers to the accelerated warming of the world's climate over the past 50 to 60 years, attributable to the burning of fossil fuels. Since the dawn of the industrial age, developed human societies have been burning coal, natural gas, and petroleum, ostensibly to power industry, urban development, and transportation. The excessive pumping of carbon dioxide into the atmosphere is threatening to upset the delicate balance of Nature. More carbon is now entering the atmosphere that can be removed through photosynthesis and other natural means.

The most widely recognized indicator of global climate change is the atmospheric concentration of carbon dioxide (CO_2) measured at the Mauna Loa Observatory, in Hawaii. Figure 1 shows the complete record to date, which spans the period from March 1958 to July 2015. The red curve shows the seasonal variations (the data corresponds to the Northern Hemisphere), while the black curve shows the average annual trend. This curve is referred to as the *Keeling curve*, in honor of Charles David Keeling, who started the record (Ponce, 2011).

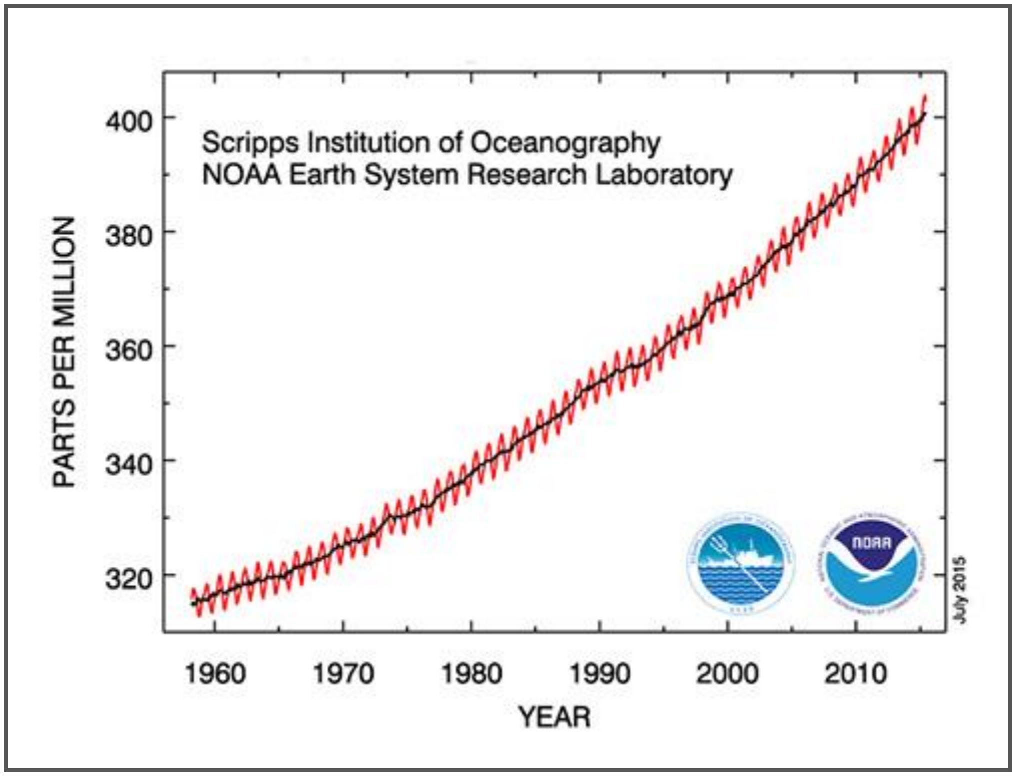

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Fig. 1 Atmospheric concentration of carbon dioxide at Mauna Loa, Hawaii.

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2. GLOBAL WARMING

It is clear from the record that the concentration of carbon dioxide, which was around 318 ppm in 1958, has now [July 2015] reached the threshold of 400 ppm, all-the-while showing a definitely upward trend (Fig. 1). These numbers show that the concentration of carbon dioxide has increased about 26% in the past 57 years of record. Most scientists believe that the rise in the Keeling curve is due to the excessive burning of fossil fuels, which, once in the atmosphere, tend to accumulate, since there is no natural way of returning to the Earth (in the quantities in which it is being burned). In effect, the atmosphere is seen to be acting as a convenient dump for the excess carbon.

How does the atmospheric concentration of carbon dioxide affect global climate change? In other words: How does an increase in atmospheric CO_2 produce global warming? To answer this question, we need to look at the constituents of the atmosphere: (a) nitrogen (78%), (b) oxygen (21%), (c) water vapor (0.4%), (d) carbon dioxide (0.04%, i.e., 400 ppm), and (e) smaller percentages of other gases. While the constituents of the atmosphere are subject to change in geologic time, they tend to be essentially constant when viewed in the timescale of human interest, say 100 years. The exception is carbon dioxide, which has increased about 26% in the past 57 years (Fig. 1).

In 1896, Svante Arrhenius published a paper entitled "On the influence of carbonic acid in the air upon the temperature of the ground," where he pionereed the science of global warming (Arrhenius, 1896). He reasoned that the air retains heat in two ways:

1. By diffusion as the heat passes through the air, and
2. By selective absorption, since some atmospheric constituents absorb great quantities of heat.

Nitrogen (N_2) and oxygen (O_2), the atmosphere's primary constituents, are homonuclear diatomic molecules, too tightly bound together to be able to absorb heat through vibration. The selective absorption of heat is accomplished by carbon dioxide (CO_2) and water vapor (H_2O), two non-diatomic molecules which are present in the air in small quantities. These two molecules consist of two elements and more than two atoms, bound together loosely enough to be able to vibrate somewhat with the absorption of infrared radiation (i.e., the heat coming from the ground) (Fig. 2). Eventually, the vibrating molecule will emit the radiation again and it will likely be absorbed by yet another molecule. This absorption-emission-absorption cycle serves to keep part of the heat near the Earth's surface, insulating the latter from the cold of outer space. Other heat-absorbing non-diatomic compounds such as methane (CH_4) and nitrous oxide (N_2O) are also present in the atmosphere, albeit at much smaller concentrations.

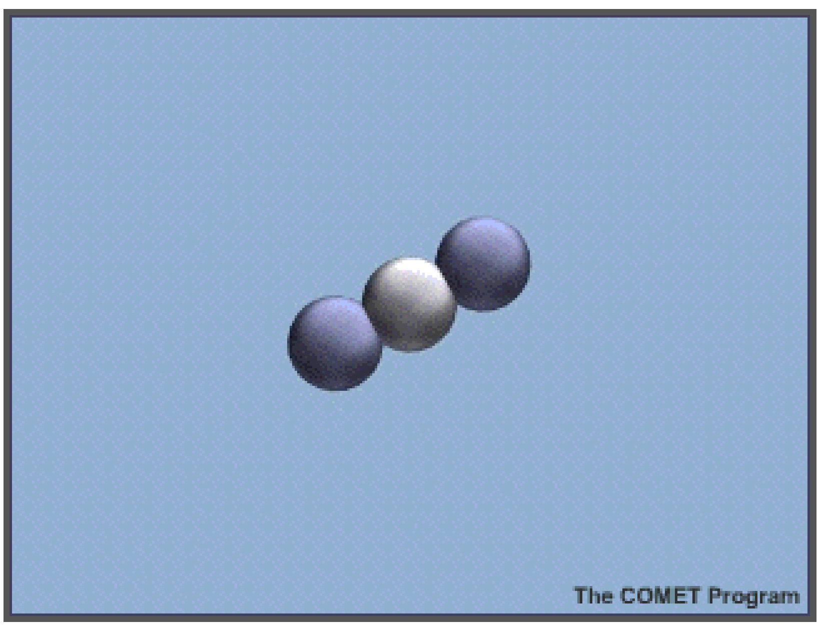

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Fig. 2 Heat absorption of carbon dioxide molecule through vibration.

Of the two more important non-diatomic constituents of the atmosphere, water vapor (H_2O) and carbon dioxide (CO_2), only the later has a clear anthropogenic origin. Water vapor varies in the atmosphere in largely unpredictable ways, with no discernible human influence in the timescale of analysis (the past 60 years).

The selective absorption of heat through vibration by the non-diatomic components of the atmosphere effectively means that these serve as a blanket to retain heat near the Earth's ground surface, impeding its diffusion into stellar space. Their concentration is an indication of the thickness of the blanket; thus, a carbon dioxide concentration of 400 ppm ought to be about 26% more effective in retaining heat than a concentration of 318 ppm.

That this is indeed the case is demonstrated by the record of global land-ocean temperatures shown in Fig. 3. This figure shows global surface temperature anomalies (black squares) and their 5-year running means (red curve), using a base period of 1950 to 1980. The data indicates that global surface temperatures have increased about 0.6°C since 1960.

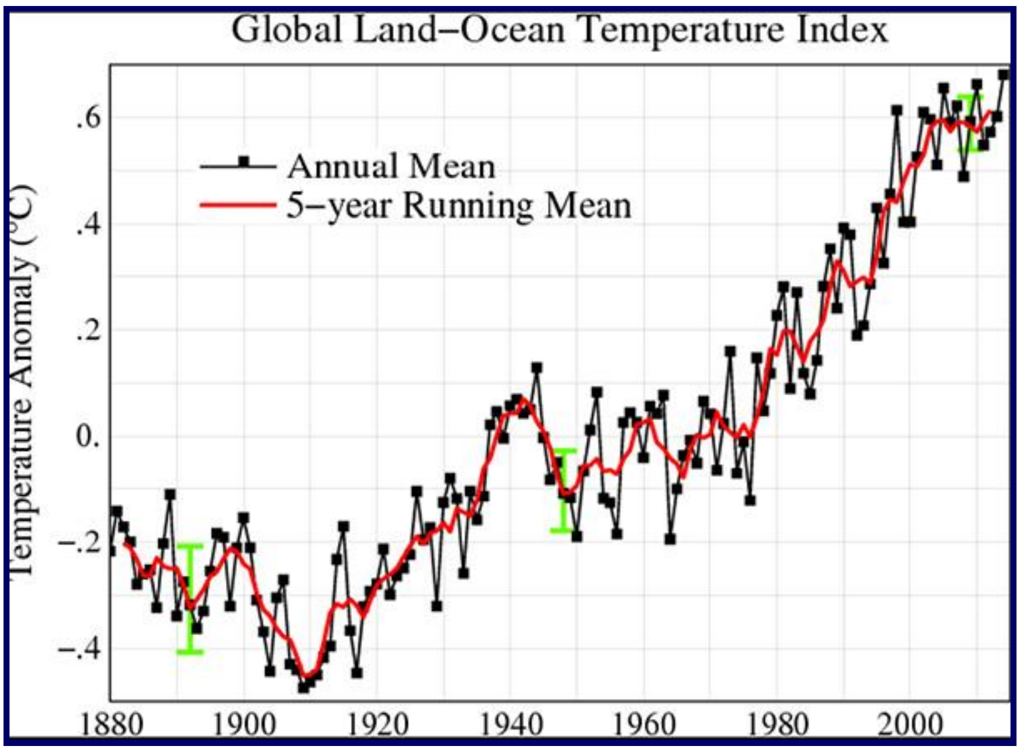

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Fig. 3 Global land-ocean temperature index.

Thus, there is very good reason to believe that Fig. 2 is the cause and Fig. 3 the effect, and that the Earth's surface air temperatures are increasing. Since the burning of fossil fuels is the only process that can pump carbon dioxide to the atmosphere in such great quantities, it is readily seen how this activity, which has taken place in earnest in the past 50 years, may be regarded as the culprit.

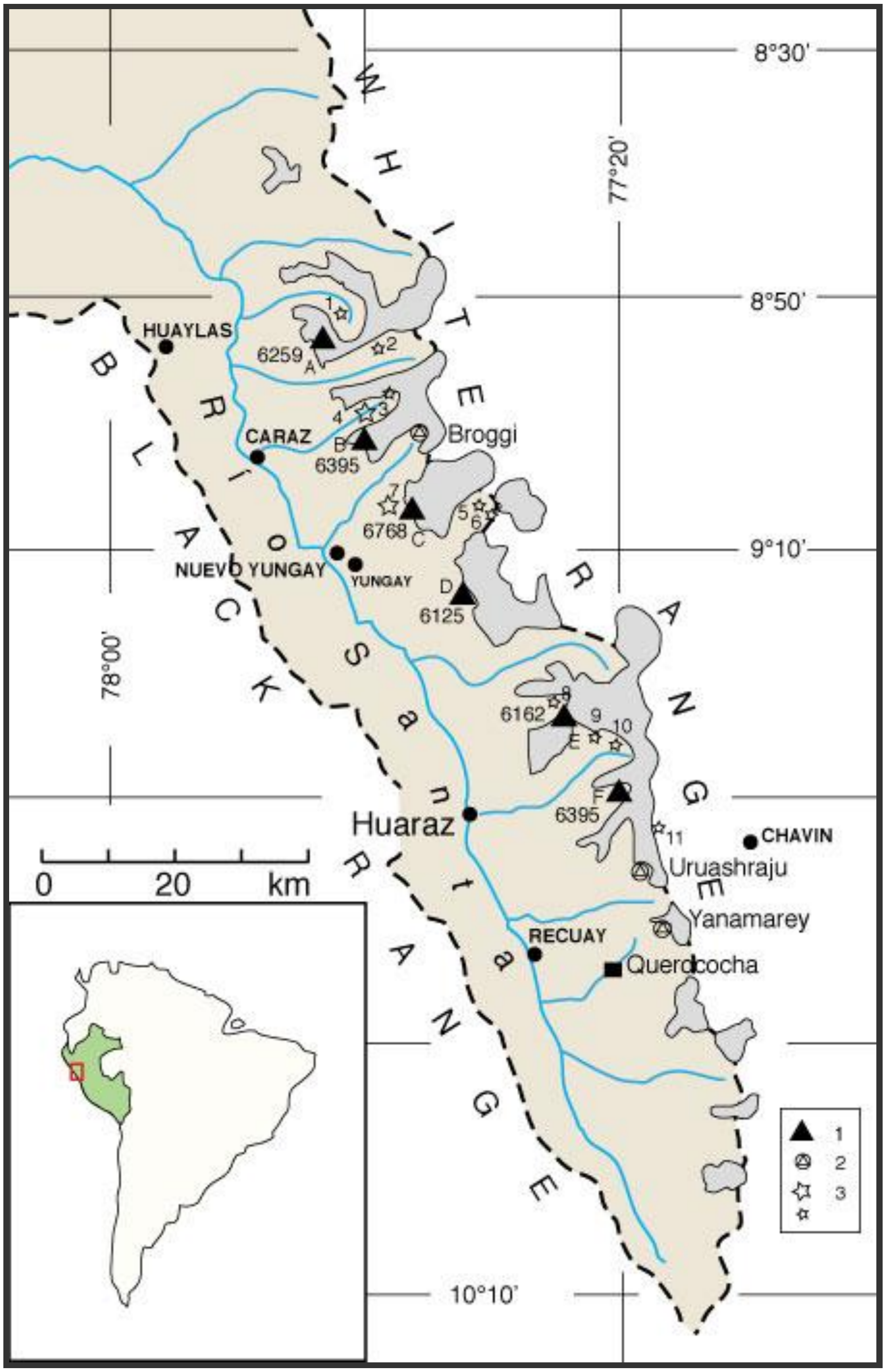
The effect that protracted global warming will have on the global hydrologic cycle, on the regional weather and climate, and on the world's icecaps and glaciers is now beginning to be examined. In this paper, we focus on the White Range of Peru, which features the largest concentration of glaciers in the tropics. It is clear that global warming is bound to significantly affect these glaciers.

3. THE WHITE RANGE OF PERU

The White Range of Peru is located between 8°23' and 10°02' South Latitude, encompassing 122 mountain peaks, with elevations above 5,000 m, of which 15 of them lie above 6,000 m. (Data Bank on Glaciers, 2015). In 1970, the aerial extent of the glaciers was measured at 723 km^2, which comprised 26% of the area covered by all tropical glaciers (in Peru, Bolivia, Ecuador, Colombia, Venezuela, Africa, and Indonesia) (Ames and Francou, 1995).

There are 755 glaciers in the White Range [2015] (Nelson Santillan, personal communication). As it is usual in the tropics, these glaciers are small in areal extent, averaging 1 km^2, with only 12 of them exceeding 5 km^2. Figure 4 shows the salient geographical features of the White Range. This figure shows: (a) the outline of the basin of the *Rio Santa* (Santa River), (b) the location of the snow-capped White Range along the eastern boundary, and (c) the snow-free Black Range along the western boundary. The following are noted :

1. Principal mountain peaks above 6,000 m elevation: Table 1 (a);
2. Cities in the vicinity;
3. Meteorological station at Querococha;
4. Glaciers Broggi, Uruashraju, and Yanamarey; and
5. Lakes with risk of avalanche: Table 1 (b).



Modified from Ames and Francou

Fig. 4 Salient geographical features of the White Range of Peru.

Table 1 (a). Peaks above 6,000 m elevation.[1]		
Label	**Name**	**Elev. (m)**
A	Santa Cruz	6,259
B	Huandoy	6,395
C	Huascaran	6,768
D	Hualcan	6,125
E	Ranrapalca	6,162
F	Huantsan	6,395

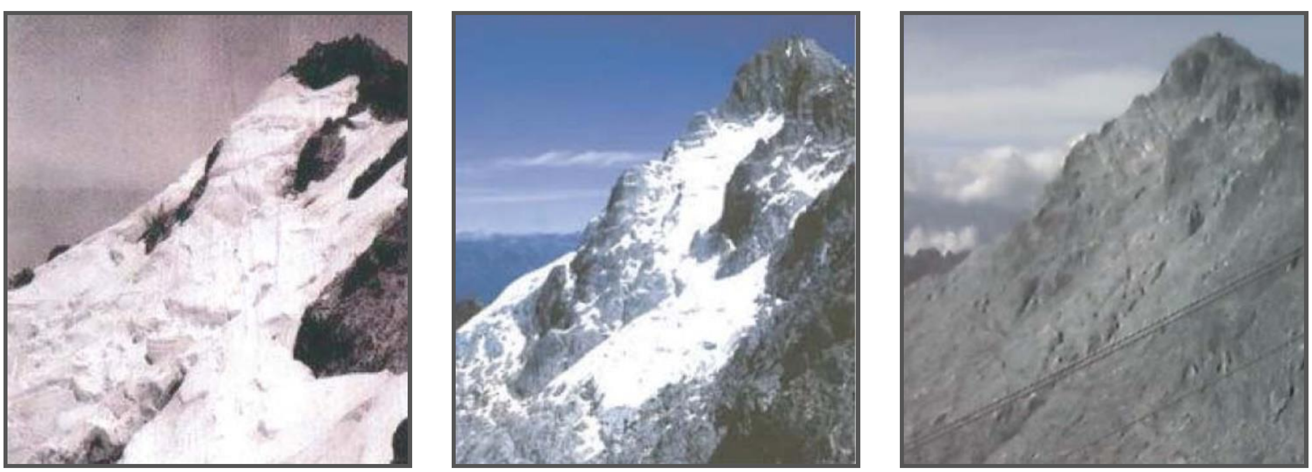
[1] **Source:** Ames and Francou, 1995, *op. cit*.

Table 1 (b). Lakes with risk of avalanche. [1]	
No.	**Name**
1	Safuna
2	Arhuaycocha
3	Milluacocha
4	Palcacocha
5	Tullparaju

[1] ***Source:*** Nelson Santillán Portilla, Autoridad Nacional del Agua, Lima, Perú.

4. EFFECTS OF GLOBAL CLIMATE CHANGE

The effects of global climate change on the health of tropical glaciers is predictable. There is and will continue to be glacier melt, which, depending on the extent of the recession, may partially or totally compromise glacier integrity. The glaciers of the White Range are large compared to other glaciers of the tropics and, therefore, are likely to last longer. Smaller glaciers in Venezuela, Colombia, and Ecuador are either in frank recession or have already disappeared completely (Fig. 5) (Vuille, 2013).



1910 1988 2008

Fig. 5 Timed sequence of the Espejo Glacier, at Pico Bolivar, Venezuela, showing the progressive
melting [Photos courtesy of Eduardo Carillo, as cited by Vuille (2013)].

Glacier recession. The effects of global climate change on the White Range of Peru have been documented since the late 1960s. Ames and Francou (1995) report on measurements on the Broggi, Uruashraju, and Yanamarey glaciers shown in Table 2, pointing to increasing recession rates since 1982 (see Fig. 4 for the precise geographical locations of these glaciers). Moreover, recent studies of the Yanamarey glacier have shown that the average recession rate in the six-year period from 2003 to 2009 has exceeded 30 m/yr (Bury *et al.*, 2010). Based on current recession rates, Bury *et al.* (*op. cit.*) have projected that the Yanamarey glacier will disappear within 50 years (Fig. 6).

Table 2. Measured recession rates of three White Range glaciers.

Period	Recession rate (m/yr)		
	Broggi	Uruashraju	Yanamarey
1932-48	18.1	-	-
1949-81	11.0	8.0	6.0
1982-93	30.0	19.6	18.6

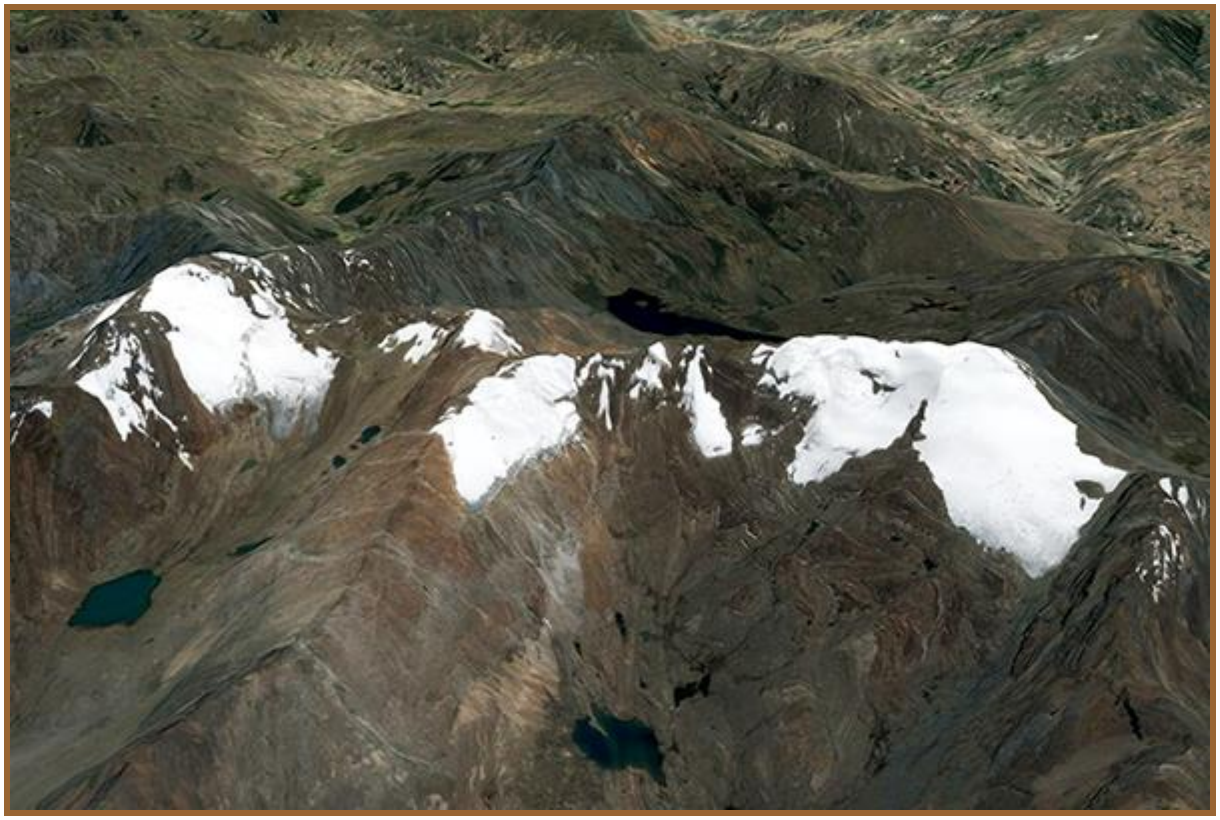


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Fig. 6 (a) Aerial perspective of the Yanamarey glacier, pointing towards the northeast [2015].

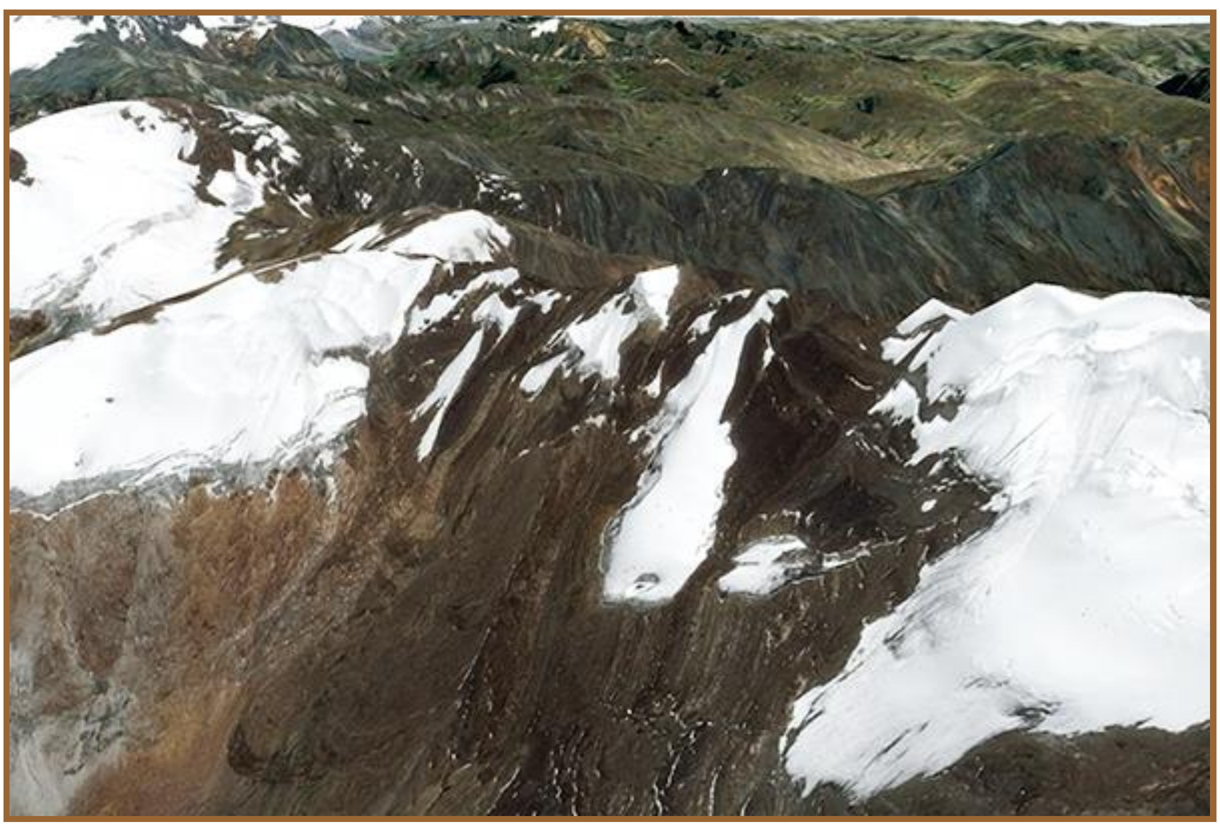

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Fig. 6 (b) Closeup of the Yanamarey glacier, showing most recent melt [2015].

Figure 7 shows Lake Querococha, located west and downstream of the Yanamarey glacier, with the glacier visible in the background (see Fig. 4 for a precise location of Lake Querococha). This figure, taken in 2003, shows that at that time the glacier may have been much greater; compare with Fig. 6 (a).

Fig. 7 Lake Querococha, with the Yanamarey glacier visible in the background (photo taken in August 2003).

Several studies have sought to estimate the extent of glacier recession in the White Range. Using remote sensing, Racoviteanu et al. (2008) found that the total glacier surface decreased by 22.4% between the years 1970 and 2003, amounting to an average rate of 0.68% yr-1. In contrast, Baraer et al. (2012) have documented recession rates of 0.62% yr-1 for the much longer period of 1930-2009. Significantly, for the period 1990-2009, the Baraer *et. al.* data (*op. cit.*) indicated a rate of 0.81% yr-1, pointing to an acceleration of the recession rate in recent times. Moreover, a recent study has shown that the loss of glacier surface in the White Range between the period 1970-2003 has been 27% (Autoridad Nacional del Agua, 2014).

Related effects. The effects of global climate change on the White Range (and other glaciers of the tropical zone) are not limited to glacier recession. The effects encompass a gamut of related changes in different fields, including: (a) climatology, (b) geomorphology, (c) hydrology, (d) ecology, and (e) socioeconomics. These changes are described in Table 3.

Table 3. Effects of global climate change on the White Range and vicinity.

Field	Effect	Description
Climatology	Temperature increase	Temperatures have risen substantially in the past 50 years.
	Glacier recession	Glaciers have receded substantially in the past three to five decades.
Geomorphology	Formation of lakes	The number of glacial lakes in the vicinity has increased substantially (more than 70% in the past 50 years).
	Glacial lake outburst	Glacial lake outburst floods remain a threat to life and property in the downstream valleys.
Hydrology	Seasonal	In the short term, changes in seasonal runoff are taking place as the additional melt increases the baseflow.
	Annual	In the medium term, increased surface runoff is taking place as the additional melt reaches the stream network.
	Pluriannual	In the long term, reductions in surface runoff are bound to take place, as basin moisture is no longer being stored as snow and ice, to be gradually released as snowmelt.
Ecology	On life zones	At least ten biological life zones have been identified, which will tend to shift.
	On floral species	More than 50 groundcover and 18 woody and herbaceous species that have been identified will be affected.
	On faunal species	More than 70 animal species will be affected.
Socioeconomics	On human settlement	The people living in the Callejon de Huaylas and vicinity will be directly affected.

The changes in the White Range are currently occurring and are expected to continue well into the future. Glacier coverage has declined by more than 25% since 1970; furthermore, between 1951 and 1999, average temperature has increased 0.35°-0.39° per decade, significantly at an accelerating pace (Bury *et al.*, 2010).

New glacial lakes. Glacial lakes develop as a direct result of glacier melt. Large glacial lakes, particularly those with more than 5 million cubic meters of water, pose significant risks for local residents and infrastructure, in view of the scale of the destruction that would ensue from an outburst flood. In 1953, a comprehensive glacial lake inventory revealed the existence of 223 lakes in the White Range. Thirty-five (35) of the 223 lakes were classified as unstable, with twenty-three (23) of them requiring immediate attention (Carey, 2010).

With protracted global climate change and the rise in average temperature, the number of glacial lakes in the White Range has continued to increase. In 1962, a second inventory resulted in a total of 263 lakes; by 1997, the number of lakes had increased to 374. Presently, the number of glacial lakes in the White Range is more than 800 (Table 4).

Figure 8 shows the Nevado Hualcán, near Carhuaz, a typical example of a glacier featuring many glacial lakes.

Table 4. Increase in the number of glacial lakes in the White Range.

Year	No. of lakes [1]	Increase in the number of lakes within the indicated period	Annual rate of increase in the number of lakes
1953	223	-	-
1962	263	40	4.0
1983	314	51	2.4
1997	374	60	4.3
2015	830 [2]	453	25.3

[1] Carey, M., 2010, op. cit.
[2] Nelson Santillán Portilla, Autoridad Nacional del Agua, Lima, Perú.

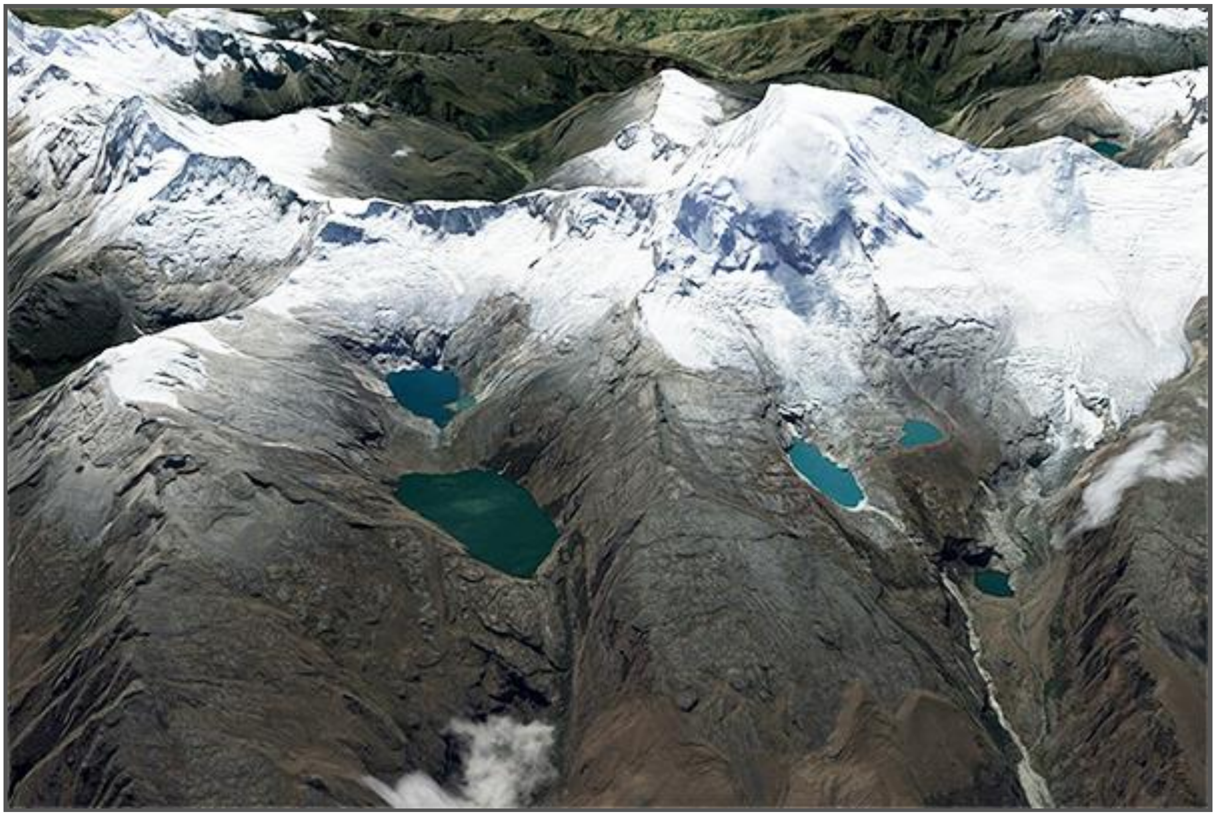

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Fig. 8 Nevado Hualcán, showing several glacial lakes on its west side.

Role of glacier melt. The growing role of melt during the dry season may be surmised. Overall, runoff has three sources: (1) melting of glaciers, (2) direct runoff, which comes from precipitation, and (3) baseflow. In the Cordillera Blanca, Baraer *et al.* (2008) have reported significant differences between the composition of the average annual runoff and that corresponding to the dry season. For example, in Lake Querococha (Fig. 7), data from Baraer et al. (*op. cit.*) indicate that during the dry season melt volume is half the volume of runoff (50%), while the average annual volume of melting is only a quarter (25%) (Table 4).

Table 5. Annual vs dry-season differences in runoff sources in the Yanamarey watershed.

Timespan/ Season	Period	Runoff source (%)		
		Melt	Surface runoff	Baseflow
Annual	1998-1999	**25**	60	15
Dry season	June-August 1998	**50**	3	47

Social impact. The glaciers of the Cordillera Blanca have sustained the population of the Upper Rio Santa for millennia (Pearsall, 2008). The entire region is referred to locally as the *Callejon de Huaylas* (Huaylas Corridor), due to its elongated shape along the river, flanked by the White Range to the east and the Black Range to the west (Fig. 4). The population, consisting of about 320,000 people, is distributed among hundreds of small rural settlements, with approximately half of the people living in major urban clusters along the Rio Santa, including the cities of Huaraz, Yungay, Caraz, Carhuaz, and Recuay. Huaraz, a major urban center, with about 120,000 people, is the capital of the department of Ancash (Fig. 9).

Fig. 9 The city of Huaraz, in the Callejon de Huaylas.

Glacial lake outburst floods. The danger of glacial lake outburst floods (GLOF) and avalanches remains a threat in the White Range, and very likely to be exacerbated by continuing global climate change. Table 6 documents the most important glacial lake outburst floods of the past 75 years. Carey (2010) has documented a total of twenty-nine (29) GLOFs since the year 1725, with the majority of them (26) occurring in the past century alone (since 1917). The cities affected have been Huaraz, Yungay, Caraz, Carhuaz, Huallanca, and Chavín de Huantar.

Table 6. Important glacial lake outburst floods in the White Range in the past 75 years.					
Yr/mo/dy	**Glacier**	**Source maximum elevation (m)**	**Lake**	**Affected city**	**Effect**
1941 December 13	Palcaraju	6,175	Palcacocha Fig. 9 (a)	Huaraz	15-m high debris flow avalanche descended on the capital city, killing 5,000 people
1945 January 17	Huantsán	[Not determined]	Ayhuiñaraju and Carhuacocha	Chavín de Huantar	1 million m^3 of water, ice, and debris buried the ruins at Chavin and destroyed two-thirds of the town, killing 500 people
1950 October 20	Alpamayo	5,615	Jankarurish Fig. 9 (b)	Huallanca	3.5 million m^3 of water, ice, and snow destroyed important hydroelectric infrastructure along the Santa River, killing 200 people
1951 October 27	Artesonraju	5,934	Artesoncocha Fig. 9 (c)	Caraz	Outburst flood sent 2.8 million m^3 of water into Lake Parón, threatening Caraz
1954 June 18	Tullparaju	5,825	Tullpacocha Fig. 9 (d)	Huaraz	Outburst flood threatens Huaraz
1959 December 8	Tullparaju	5,825	Tullpacocha Fig. 9 (d)	Huaraz	Outburst flood threatens Huaraz
2003 March 19	Palcaraju	6,175	Palcacocha Fig. 9 (a)	Huaraz	Small outburst flood threatens Huaraz and causes minor damage

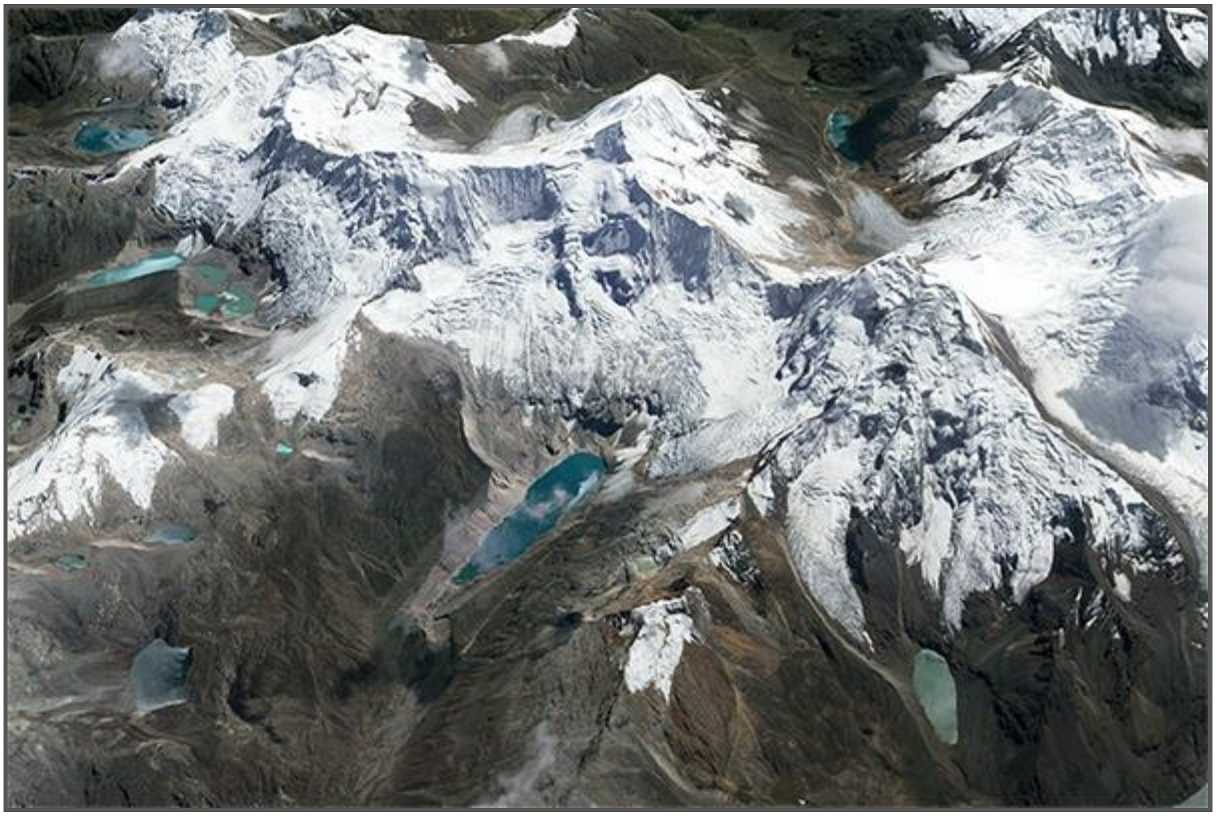

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Fig. 9 (a) Palcaraju Glacier, with Lake Palcacocha in the foreground.

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Fig. 9 (b) Alpamayo Glacier, with Lake Jankarurish in the foreground.

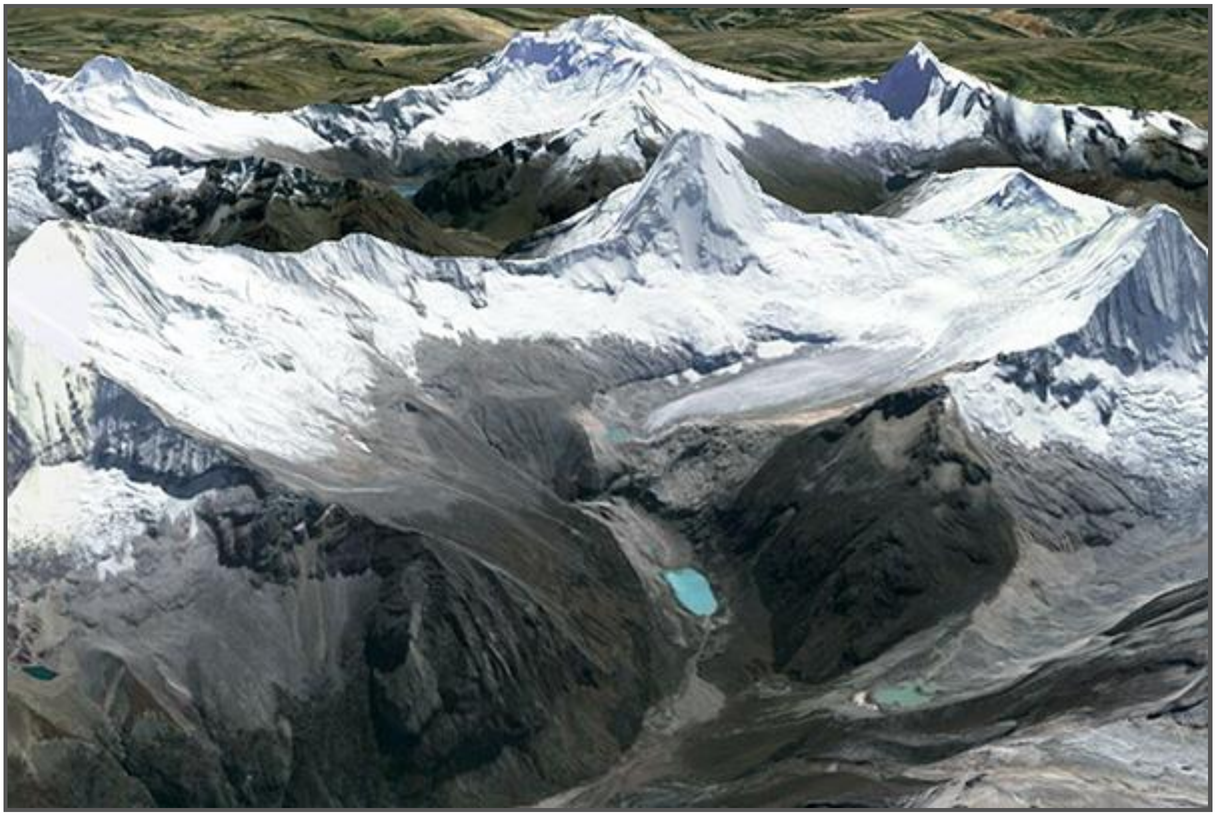
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Fig. 9 (c) Artesonraju Glacier with Lake Artesoncocha.

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Fig. 9 (d) Tullparaju Glacier with Lake Tullpacocha.

5. CONCLUDING REMARKS

Global climate change, specifically anthropogenic global warming, threathens to upset the delicate balance of Nature, wherein the global climate is determined by the concentration of non-diatomic gases in the atmosphere, among them, significantly, carbon dioxide (CO_2). The sustained warming of the past 50 years has produced a host of negative effects. In this paper we highlight the effect that global warming has had on the tropical glaciers, including melting, recession, and their possible eventual disappearance. This places in jeopardy the continuance of a wide array of natural services, among them the supply of water resources, the conservation of flora and fauna, the aesthetics of the natural landscape, and the societal activities of tourism, mountaineering and alpinism.

We specifically focus on the White Range of Peru, a resource of global importance and significant aesthetic value. Life of all kinds stands to be negatively affected by protracted global warming and the impairment of the White Range.

The following conclusions are drawn from this study:

- The concentration of carbon dioxide in the atmosphere has reached 400 ppm at the present time [July 2015]. The increase has been mostly attributed to the excessive burning of fossil fuels.
- Global average surface temperatures have increased about 0.6°C in the past 50 years.
- The rise in global surface temperatures has negatively affected the tropical glaciers, causing a decrease in aerial coverage. The changes have been gradual, but the rate of change appears to be increasing. Average rates of glacier recession over the period 1930-2009 have been measured at 0.62% yr-1, and over the period 1990-2009 at 0.81% yr-1. A recent official study [2014] has documented that the loss of glacier area in the White Range in the period 1970-2003 has been 27%.
- Glacier melting has caused an increase in the number of glacial lakes in the White Range. The lakes have nearly doubled in number over the past 60 years, from 223 at the time of the first inventory (1953), to more than 800 at the present time.
- Continuing glacier melting poses a significant threat of glacial lake outburst floods (GLOF). The latter consist of water, snow, ice, and debris. If not adequately controlled, these disastrous events will spell havoc and destruction in the communities located directly in the path of the floods. Urban relocation, although a sensible decision in the eyes of many, remains politically difficult.
- Many of these devastating floods have occurred in the White Range in the past 100 years (26 of them), and the chances are that they will continue to recur.
- Relevant scientific understanding, coupled with enlightened interdisciplinary management, is necessary for the national government of Peru and its partners in the international community to develop an effective strategy to cope with these threats. Sustainability being clearly out of the question, the aim remains to mitigate/reduce the effects of global warming within the next one to two generations.

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