Light energy loss and its application to estimate a global energy usage

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ABSTRACT

We are now developing a system to estimate light energy loss to space using the US DMSP (Defense Meteorological Satellite Program) data and obtained many interesting results. The satellites have solar synchronous orbits with altitude around 800 km, and continuously obtain absolute (well-calibrated) flux of terrestrial surface light.

City light ejected to space is mostly energy loss because the light is not used to illuminate objects to be seen or decorated. The total amount of its energy loss in Japan estimated by us is an order of 20 billion yen (about 200 million US dollars). We are now estimating its loss for each cities (or areas) in Japan and in the world. Further, we found a possibility to estimate energy usage of each country after obtaining a clear relation between light energy loss and electric energy usage within different areas of individual electric companies in Japan.

Therefore, we would like to conclude that our continuous estimation of city light from space are and will be creating a global information of energy usage.

Keywords: Light pollution, Energy loss, Energy usage, The DMSP, City light

1. INTRODUCTION

Recently, there are many different types of global environmental problems becoming eminent. To find those changes, many scientific researchers have made much efforts. It is clear that global problems should be studied from global observational data. To do so there was only a way to collect data from a point to the other point, but this method requires much elaborating research activities. Now, we have an another method using a satellite covering all the global surface within a few days, although its observational resolution may not be so high as that of ground-based observations.

As an astronomer, I am much interested in light pollution which makes night time sky bright and is able to destroy our good observational condition. If polluted sky brightness would be double of natural one, our telescope time would be lost down to one fourth. If it happened at the Subaru telescope at the Mauna Kea we would loose 30 billion yen (nearly equivalent to 300 million US dollars). Moreover, in a city people loose stars on celestial sphere and may have quite different understanding of our universe.

We have studied night sky brightness using ground-based photographic technique (Isobe and Kosai 1994 and 1998) and obtained a contour map of its distribution. We also obtained an intensity distribution of terrestrial surface observed by the US Defense Meteorologies Satellite Program (hereafter called as DMSP). While a ground-based observation detects light from outdoor city lighting fixtures reflected by dust and air in atmosphere, a satellite observation detects direct light from them (figure 1) but we found both distributions are quite similar (figure 2). Further, satellite observations are able to give absolute energy ejected into space. It is an energy loss.

Here, we will show what amount of light energy is lost and changes depending on time at each city selected in the world and also how many percentage of electric energy is lost for cases of Japanese electric companies. Finally, we will suggest how efficient this work of light energy loss is to solve a global energy and environmental problems.

2. THE DMSP OBSERVATIONS

Our preliminary reduction results have already been published in different papers (cf. Isobe and Hamamura 1998, 2000). Here, we will briefly show some observational parameters.

The DMSP satellite firstly launched in 1972 and then continuously launched till now. Sometimes, multiple satellites sent and are sending observed digital data to the ground stations. Since these are military missions, the US Air Force did not release those original data to academic researchers, and one could obtained photographic images, from which Sullivan (1988) produced a famous picture of "The Earth at Night" and Nakayama (1993) made it further fine adjustment to a geographical map. From 1993 after a collapse of Soviet Union the US Air force started to release those digital data. Unfortunately since

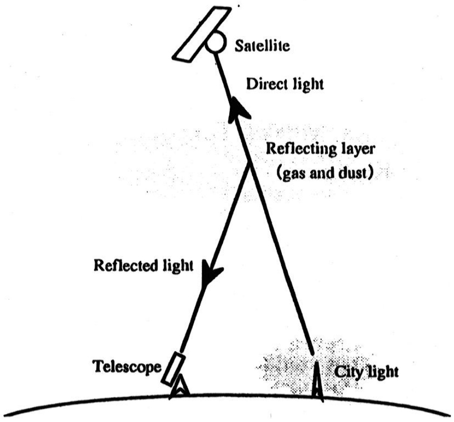


Figure 1. A Schematic figure showing light reflected by atmospheric dust and air and that directly directing to a satellite detector.

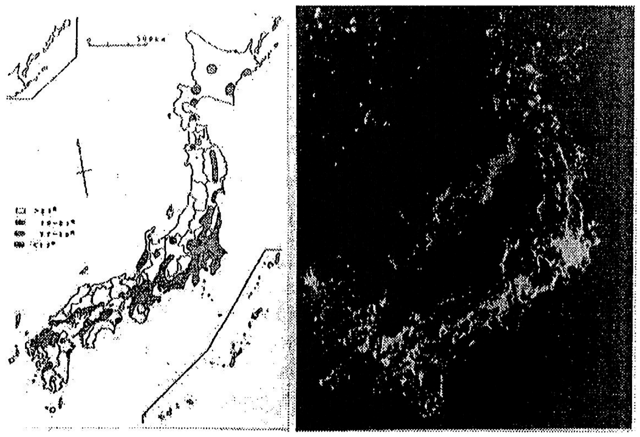


Figure 2. Distributions of sky brightness obtained from the ground-based observations (left figure) and of brightness on terrestrial surface observed by the DMSP (right figure).

Table 1. Date when low gain data are available.

1996.Mar	18	20	21	22	23					
1997.Jan	5	6	7	8	9	10	11	12	14	
1997.Feb	3	4	5	6	7	8	9	10	12	13
1999.Jan	18	19	20							
1999.Feb	13	14	15	16	17	18	19			
1999.Mar	14	15	16	17	18	19	20			
1999.Apr	13	14	15	16	17	18	19			
1999.May	12	13	14	15	16	17	18			
1999.Jun	10	11	12	13	14	15	16			
1999.Jul	10	11	12	13	14	15	16			
1999.Aug	8	9	10	11	12	13	14			
1999.Sep	6	7	8	9	10	11	12			
1999.Oct	6	7	8	9	10	11	12			
1999.Nov	14	15	16	17	18	19	20			
1999.Dec	4	5	6	7	8	9	10			

those detector sensitivity is too high and its dynamic range is only 6 bits, images of the most large cities are saturated. We made the first stage works using these saturated data. After several works (ex. Elvidge et al 1997, Isobe and Hamamura 1998), a request of the DMSP observations at low gain made by the US National Geographic Data Center was accepted and the low gain data were obtained on data shown in table 1. Now, we can use some number of non-saturated data except central parts of big cities.

Output signal is a 6 bit digital data covering absolute energy flux from 5.03 x 10^{-9} watt/cm^2/st/micrometer to 3.17 x 10^{-7} watt/cm^2/st/micrometer. Using those observed data, energy loss integrated within each city or area is calculated. Although we can evaluated it at limited number of cities and areas till now because of a shortage of working manpower, we will continuously reduce those data which are supplied year by year.

3. ENERGY LOSS OF EACH CITY IN THE WOULD

Figures 3 and 4 show light distributions at night time in Japan and its enlarged areas of Shikoku and Chugoku, respectively. Since this is a low gain data, we can identify each individual city and then obtain its integrated light energy, which is energy loss. Table 2 shows energy loss for the cities evaluated in our current evaluation processes. One should remind that since all the reduced data obtained during winter time in the northern hemisphere, there were some cases when snow covered surface of land and had high reflectivity to downward light. It is clearly shown for a case of Sapporo in the northern island.

Figure 5 shows some relation between energy loss and population in each city. In this Asian countries, there is no simple correlations, which suggest there are much different lighting fixtures from one city to the others and also difference of economic developments.

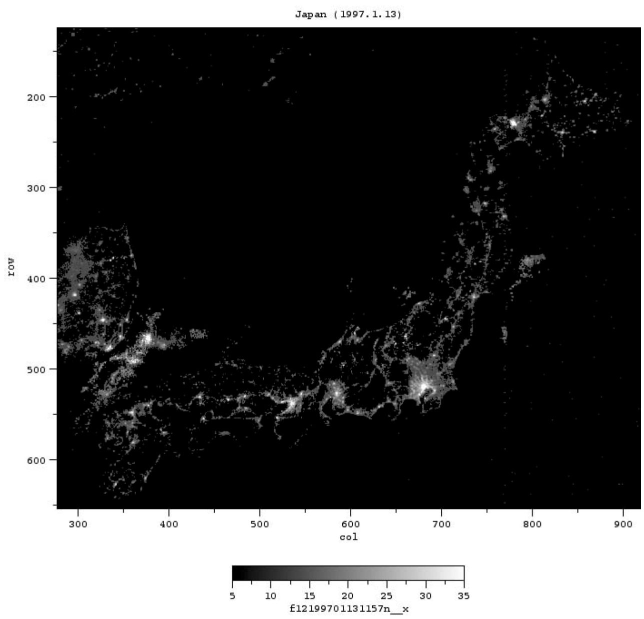


Figure 3. Brightness distribution at night time on the Japanese area of terrestrial surface obtained from low gain data of the DMSP.

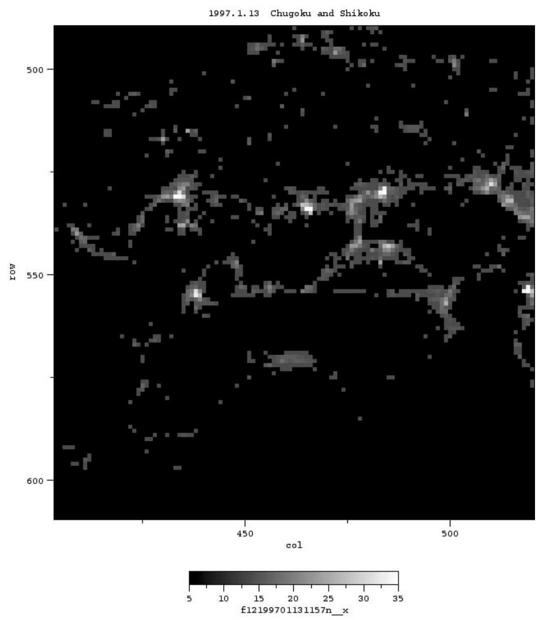


Figure 4. Same as figure 3, but enlarged one of Chugoku and Shikoku regions.

Table 2a. Light energy loss at night time of each city in the world obtained from the DMSP data.

	Observed Value (10^{-8}Watt/cm^2/st/μm)	Light Energy Loss (10^6kW・h)	Area (km^2)	Light Energy Loss/Area (10^6kW・h/km^2)
Asia				
Japan (1997.1.13)				
Sapporo	2.47×10^3	14.8	1046	1.41×10^{-2}
Sendai	7.40×10^2	4.43	463	9.57×10^{-3}
Kanazawa	5.18×10^2	3.10	543	5.71×10^{-3}
Shizuoka	4.56×10^2	2.73	528	5.17×10^{-3}
Nagoya	3.83×10^3	22.9	1519	1.51×10^{-2}
Osaka	5.85×10^3	35.1	1896	1.85×10^{-2}
Hiroshima	8.72×10^2	5.22	1001	5.21×10^{-3}
Kochi	2.39×10^2	1.43	729	1.96×10^{-3}
Fukuoka	1.56×10^3	9.35	1026	9.11×10^{-3}
Korea (1997.2.7)				
Seoul	7.07×10^3	42.4	2266	1.87×10^{-2}
Pusan	1.49×10^3	8.96	910	9.85×10^{-3}
Pyongyang	2.38	0.0143	133	1.08×10^{-4}
South East Asia(1997.2.9)				
Hong Kong	2.11×10^3	12.6	1119	1.13×10^{-2}
Manila	1.48×10^3	8.87	2272	3.91×10^{-3}
Ho-Chi-Minh	1.07×10^3	6.44	2360	2.73×10^{-3}
Phnom Penh	8.44×10^1	0.506	549	9.21×10^{-4}
Chiang Mai	3.41×10^2	2.04	598	3.42×10^{-3}
Bangkok	5.16×10^3	30.9	5712	5.41×10^{-3}
Yangon	3.71×10^2	2.22	849	2.62×10^{-3}
Kuala Lumpur	2.28×10^3	13.7	4317	3.17×10^{-3}
Singapore	2.86×10^3	17.1	3263	5.25×10^{-3}
Dacca	4.91×10^2	2.94	1227	2.40×10^{-3}
Calcutta	1.48×10^3	8.89	2660	3.34×10^{-3}
Delhi	4.48×10^3	26.8	4676	5.74×10^{-3}
Hyderabad	2.28×10^3	13.7	2644	5.17×10^{-3}
Chennai	1.88×10^3	11.3	3089	3.65×10^{-3}

	Observed Value (10^{-8}Watt/cm^2/st/μm)	Light Energy Loss (10^6kW・h)	Area (km^2)	Light Energy Loss/Area (10^6kW・h/km^2)
Europe				
England (1997.2.7)				
London	6.01×10^3	36.0	3210	1.12×10^{-2}
Birmingham	1.84×10^3	11.0	1168	9.43×10^{-3}
Manchester	2.03×10^3	12.2	1070	1.14×10^{-2}
Liverpool	9.20×10^2	5.51	505	1.09×10^{-2}
Newcastle	1.12×10^3	6.71	693	9.68×10^{-3}
Middlesbrough	7.57×10^2	4.54	510	8.89×10^{-3}
Glasgow	1.50×10^3	8.99	1374	6.54×10^{-3}
Edinburgh	5.15×10^2	3.08	447	6.90×10^{-3}
Bristol	4.11×10^2	2.46	277	8.90×10^{-3}
Plymouth	2.35×10^2	1.41	277	5.07×10^{-3}
Southampton	3.30×10^2	1.98	389	5.08×10^{-3}
Aberdeen	2.96×10^2	1.77	255	6.94×10^{-3}
Leicester	4.11×10^2	2.46	385	6.40×10^{-3}
Belfast	2.10×10^2	1.26	774	1.62×10^{-3}
Dublin	1.06×10^3	6.36	1423	4.47×10^{-3}
France(1997.1.13)				
Paris	8.08×10^3	48.4	4521	1.07×10^{-2}
Rouen	5.56×10^2	3.33	579	5.75×10^{-3}
La Havre	4.05×10^2	2.43	498	4.87×10^{-3}
Lyon	2.89×10^3	17.3	2072	8.37×10^{-3}
Clermont-Ferra	9.73×10^2	5.83	67	8.70×10^{-2}
Marseille	9.20×10^2	5.51	822	6.70×10^{-3}
Toulouse	1.11×10^3	6.68	1285	5.20×10^{-3}
Bordeaux	8.92×10^2	5.34	840	6.36×10^{-3}
Nantes	7.43×10^2	4.45	701	6.34×10^{-3}
Greece (1997.2.5)				
Athinai	2.49×10^3	14.9	1837	8.11×10^{-3}
Tessaloniki	6.67×10^2	4.00	711	5.63×10^{-3}
Larisa	1.13×10^2	0.674	219	3.08×10^{-3}
Volos	1.25×10^2	0.749	210	3.57×10^{-3}

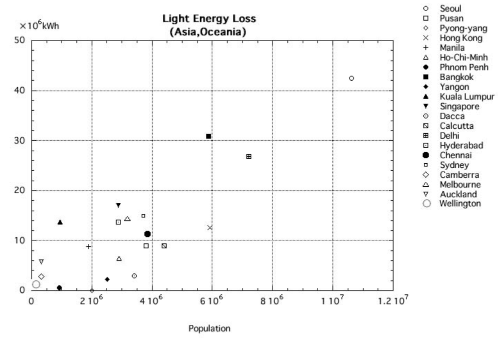
Table 2b. Light energy loss at night time of each city in the world obtained from the DMSP data.

	Observed Value (10^{-8}Watt/cm^2/st/μm)	Light Energy Loss (10^{6}kW・h)	Area (km^2)	Light Energy Loss/Area (10^{6}kW・h/km^2)
Lamia	65.6	0.393	148	2.66×10^{-3}
Iraklion	1.06×10^{2}	0.637	273	2.33×10^{-3}
(1997.1.13)				
Amsterdam	1.07×10^{3}	6.43	367	1.75×10^{-2}
Leiden	2.16×10^{2}	1.29	138	9.35×10^{-3}
Bruxelles	9.64×10^{2}	5.78	536	1.08×10^{-2}
(1997.2.3)				
Wein	1.20×10^{3}	7.19	1080	6.66×10^{-3}
Budapest	1.58×10^{3}	9.44	1331	7.09×10^{-3}
Praha	1.26×10^{3}	7.55	1020	7.40×10^{-3}
Bratislava	4.25×10^{2}	2.55	389	6.56×10^{-3}
Warszawa	1.47×10^{3}	8.81	950	9.27×10^{-3}
Dresden	9.23×10^{2}	5.53	1162	4.76×10^{-3}
Brno	4.02×10^{2}	2.41	384	6.28×10^{-3}
Krakow	7.35×10^{2}	4.40	592	7.43×10^{-3}
Milano	2.32×10^{3}	13.9	1434	9.69×10^{-3}
Zagreb	4.78×10^{2}	2.86	380	7.53×10^{-3}
Turkey (1997.2.9)				
Ankara	9.94×10^{2}	5.95	1909	3.12×10^{-3}
Antalya	1.64×10^{2}	0.984	697	1.41×10^{-3}
Istanbul	2.03×10^{3}	12.2	3602	3.38×10^{-3}
Bursa	2.54×10^{2}	1.52	648	2.35×10^{-3}
Izmir	4.87×10^{2}	2.92	1078	2.71×10^{-3}
Adana	2.90×10^{2}	1.74	742	2.34×10^{-3}
Kayseri	3.98×10^{2}	2.38	806	2.95×10^{-3}
Konya	1.95×10^{3}	1.17	554	2.11×10^{-3}
Middle East (1997.1.9)				
Tel Aviv-Yafo	1.72×10^{3}	10.3	813	1.27×10^{-2}
Jerusalem	7.40×10^{2}	4.43	511	8.67×10^{-3}
Amman	8.77×10^{2}	5.25	478	1.10×10^{-2}
Haifa	5.53×10^{2}	3.31	253	1.31×10^{-2}
Damascus	4.98×10^{2}	2.98	320	9.31×10^{-3}
Beirut	6.48×10^{2}	3.88	464	8.36×10^{-3}
Baghdad	9.39×10^{2}	5.62	1510	3.72×10^{-3}
Africa				
Egypt (1997.2.5)				
Cairo	4.51×10^{3}	27.0	1968	1.37×10^{-2}
Alexandria	6.52×10^{2}	3.90	818	4.77×10^{-3}
Ismailiya	2.88×10^{2}	1.73	273	6.34×10^{-3}
Suez	3.38×10^{2}	2.02	264	7.65×10^{-3}
North America				
Canada (1997.1.12)				
Quebec	6.13×10^{3}	36.7	1767	2.08×10^{-2}
Trois Riviere	1.23×10^{3}	7.37	36	0.205
Montreal	2.32×10^{4}	139	4039	3.44×10^{-2}
Ottawa	5.44×10^{3}	32.6	1612	2.02×10^{-2}
Toronto	2.29×10^{4}	137	4330	3.16×10^{-2}
Sudbury	1.41×10^{3}	8.45	603	1.40×10^{-2}
Chicoutimi	1.28×10^{3}	7.65	400	1.91×10^{-2}
Calgary	1.39×10^{4}	83.4	1901	4.39×10^{-2}
Edmonton	9.83×10^{3}	58.9	1819	3.24×10^{-2}
U.S.A. (1997.2.4)				
New York(Long Island)	2.26×10^{4}	136	9095	1.50×10^{-2}
Philadelphia	8.10×10^{3}	48.5	2690	1.80×10^{-2}
Boston	2.51×10^{3}	15.0	1122	1.34×10^{-2}
Baltimore	4.88×10^{3}	29.2	1854	1.57×10^{-2}
Washington	6.98×10^{3}	41.8	3087	1.35×10^{-2}
Buffalo	3.34×10^{3}	20.0	1250	1.60×10^{-2}

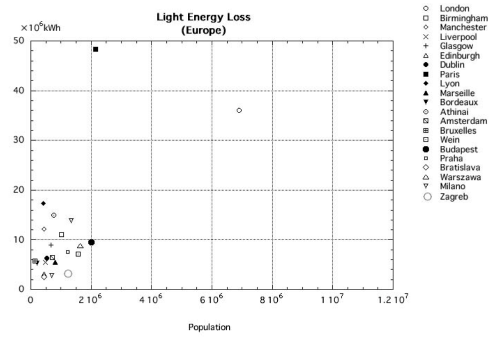
Table 2c. Light energy loss at night time of each city in the world obtained from the DMSP data.

	Observed Value (10^{-8}Watt/cm^2/st/μm)	Light Energy Loss (10^{6}kW・h)	Area (km^2)	Light Energy Loss/Area (10^{6}kW・h/km^2)
U.S.A. (1997.1.12)				
Minneapolis	2.04×10^{4}	122	4329	2.82×10^{-2}
St.Louis	1.55×10^{4}	93.0	4061	2.29×10^{-2}
Kansas City	1.19×10^{4}	71.5	4611	1.55×10^{-2}
LasVegas	6.35×10^{3}	38.0	1552	2.45×10^{-2}
Phoenix	9.18×10^{3}	55.0	4782	1.15×10^{-2}
Tucson	2.20×10^{3}	13.2	1804	7.32×10^{-3}
U.S.A.(1997.2.9)				
Sacramento	2.48×10^{3}	14.9	1926	7.72×10^{-3}
Stockton	6.15×10^{2}	3.68	499	7.38×10^{-3}
Modesto	5.05×10^{2}	3.03	447	6.77×10^{-3}
Fresno	1.11×10^{3}	6.66	998	6.67×10^{-3}
Port land	3.70×10^{3}	22.2	4918	4.51×10^{-3}
Salem	3.94×10^{2}	2.36	532	4.43×10^{-3}
Eugene	3.49×10^{2}	2.09	765	2.73×10^{-3}
Denver	4.90×10^{3}	29.4	1593	1.84×10^{-2}
Boulder	2.13×10^{2}	1.27	152	8.38×10^{-3}
Mexico (1997.1.11)				
Mexico city	1.05×10^{4}	63.0	4547	1.38×10^{-2}
Monterrey	2.48×10^{3}	14.9	2122	7.00×10^{-3}
Guadalajara	2.44×10^{3}	14.6	1644	8.89×10^{-3}
Ciudad Juarez	2.59×10^{3}	15.5	209	7.42×10^{-2}
Chihuahua	5.80×10^{2}	3.47	648	5.36×10^{-3}
Acapulco	7.16×10^{2}	4.29	848	5.06×10^{-3}
Pueblo	1.18×10^{3}	7.07	1053	6.71×10^{-3}
Leon	8.34×10^{2}	4.99	585	8.54×10^{-3}
Middle America				
(1997.2.8)				
Guadalajara	2.56×10^{3}	15.3	1260	1.21×10^{-2}
Guatemala	7.23×10^{2}	4.33	1184	3.66×10^{-3}
San Salvador	4.57×10^{2}	2.74	1038	2.64×10^{-3}
Tegucigalpa	3.23×10^{2}	1.93	489	3.95×10^{-3}
Managua	2.75×10^{2}	1.65	630	2.62×10^{-3}
San Jose	8.64×10^{2}	5.17	1141	4.53×10^{-2}
Panama	5.35×10^{2}	3.21	891	3.60×10^{-3}
Habana	3.61×10^{2}	2.16	706	3.06×10^{-3}
Kingston	7.33×10^{2}	4.39	891	4.93×10^{-3}
South America				
(1997.2.9)				
Brasilia	1.07×10^{3}	6.40	5387	1.19×10^{-3}
Rio de Janeiro	7.86×10^{3}	47.1	10615	4.44×10^{-3}
Sao Paulo	6.98×10^{3}	41.8	5676	7.37×10^{-3}
(1997.2.12)				
Santiago	2.88×10^{3}	17.3	3272	5.27×10^{-3}
Buenos Aires	9.48×10^{3}	56.8	6597	8.61×10^{-3}
Montevideo	1.62×10^{3}	9.69	3804	2.55×10^{-3}
Oceania				
Australia(1996.3.22)				
Sydney	2.50×10^{3}	15.0	4310	3.48×10^{-3}
Camberra	4.63×10^{3}	2.78	1223	2.27×10^{-3}
Newcastle	3.98×10^{3}	2.38	886	2.69×10^{-3}
Brisbane	1.82×10^{3}	10.9	3659	2.98×10^{-3}
Gold Coast	2.86×10^{2}	1.72	970	1.77×10^{-3}
Melbourne	2.41×10^{3}	14.4	3781	3.82×10^{-3}
Adeleide	1.08×10^{3}	6.45	2262	2.85×10^{-3}
Perth	1.36×10^{3}	16.2	4444	3.65×10^{-3}
New Zealand(1996.3.20)				
Auckland	9.56×10^{2}	5.73	1773	3.23×10^{-3}
Wellington	2.01×10^{2}	1.20	720	1.67×10^{-3}
Cristchurch	2.81×10^{2}	1.68	1283	1.31×10^{-3}
Dunedin	4.06×10^{2}	2.43	986	2.47×10^{-3}

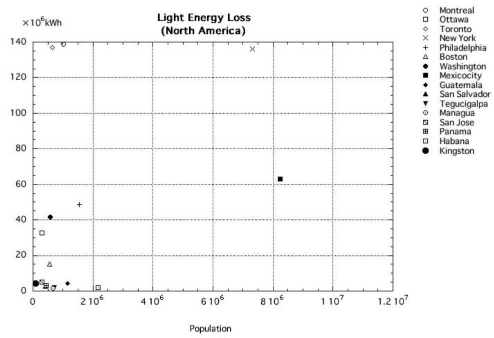
a.



b.



c.



d.

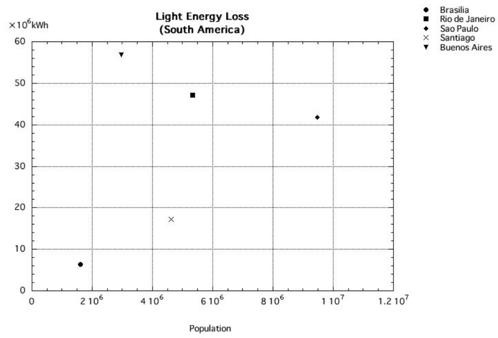


Figure 5. Relations between light energy loss in cities and those populations a. Asian area, b. Europe area, c. North American area, d. South American area.

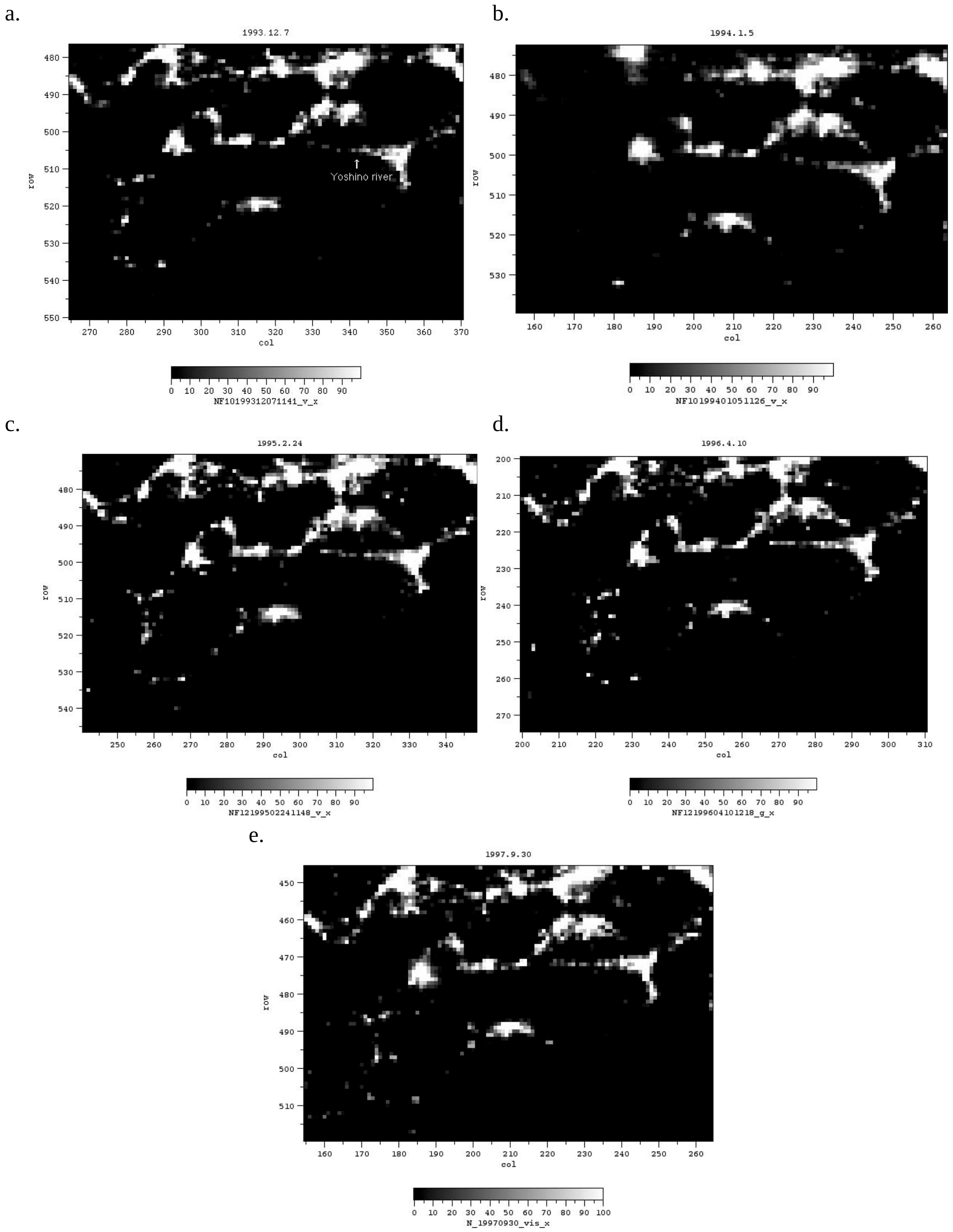


Figure 6. Brightness distribution at night time depends on time especially along the Yoshino river in Shikoku island. a. 1993, b. 1994, c. 1995, d. 1996, e. 1997.

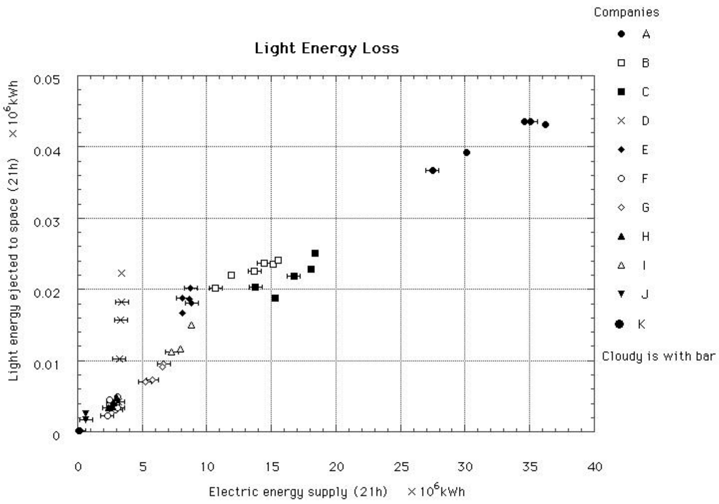


Figure 7. Relations between light energy loss obtained by us and electric energy supplied in each area by the electric supply companies.

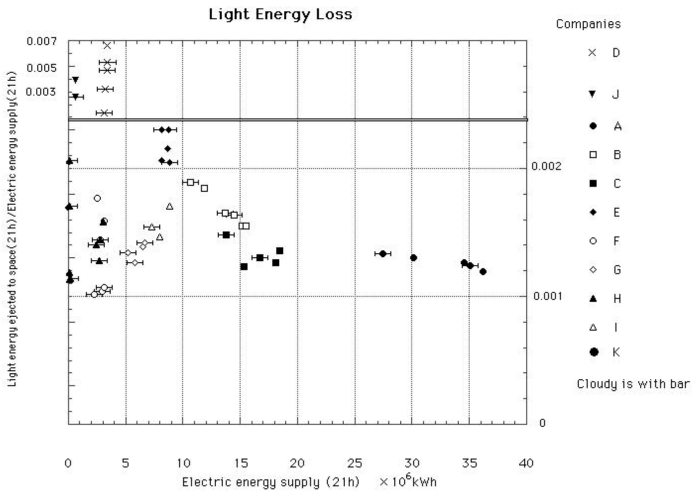


Figure 8. Percentage of light energy loss relative to electric energy supply at each observed data for each area of electric supply company.

Since we have reduced low gain data only in 1996 and 1997 (Recently, we obtained data for 1998 and 1999.), it is hard to say about its time dependence. To study it, we can use high gain data in rather small cities observed from 1993 to 1997. Figures 6a to 6d show a change of light distribution. Bright area along the Yoshino-river extended to the upper river-end year by year. If we could use low gain data spanning much long observed years, we could find change of light energy loss at many cities depending on time.

Further related data will be presented in a future paper.

4. A RELATION OF LIGHT ENERGY LOSS TO ELECTRIC ENERGY SUPPLY

There are the 9 electric companies in Japan, each of which has its own supplying area. All the companies kindly supplied us their data of electric energy supply to the areas at times when our low-gain data are available. Figure 7 show a relation of our evaluated light energy loss to the electric energy supply from each electric company. It seems to show a linear relation. To find a percentage of its light energy loss to the electric energy supply, figure 8 is drawn. Its percentage for

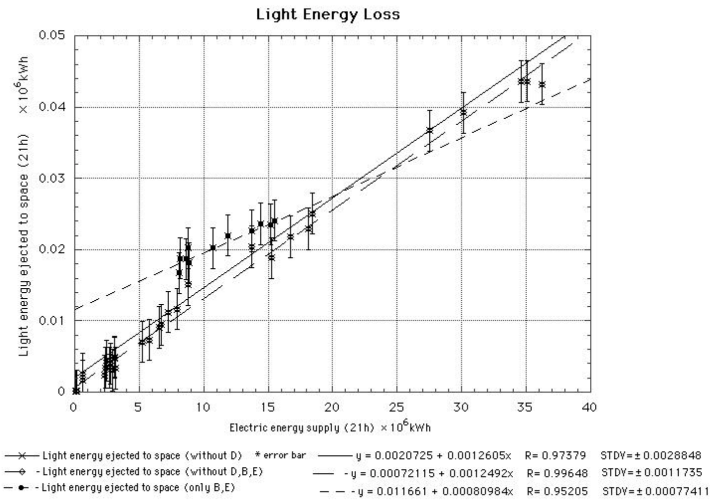


Figure 9. Least square fitting to groups of dots on figure 7. Thick line shows a line obtained from data except D and J. Dotted line is a line for those of B and E areas.

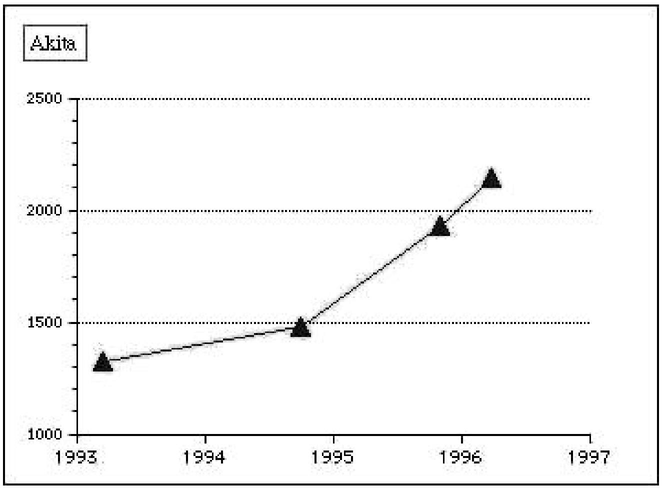


Figure 10. Time dependent energy loss for a case of Akita city in Tohoku area. Since saturated data are used vertical axis is only relative value.

each electric company is around 0.1 - 0.2 percent. This value is consistent with a fact that the Japanese total light energy loss is about 20 billion yen and the total income of electric company is about 20 trillion yen.

However, there are several areas which have much higher percentage. Those are D and J with high values and E and B with slightly high values. D was covered by snow and some mountain areas of E and B were also covered by snow. On the other hand, J has the US Air force base which independently produces its own electric energy.

Values of electric energy loss varies depending on fine or thin cloudy nights and also on working day or Sunday, but general correlation is nearly same as shown in figure 7.

There is a line (figure 9) obtained by a least square fitting to all the dots except D and J areas in figure 7. However, if one makes a same produre to the dots for E and B areas, one can get much well correlated line which crosses at a some finite value on the vertical axis. If this is true, this value of light energy loss did not originate from electric power supply but were produced some other light source such as light of car headlight. Once we draw this line, we can see another line for A which is parallel with that for E and B. To confirm this results we have to use much more data.

5. CONCLUSION

As shown in this paper, light energy loss in a city is able to be evaluated. Since the DMSP data are continuously obtained, we can find its variability month to month or at last year by year. It is visually shown in figure 6. Furthermore, since absolute value of light energy loss in each city is estimated from the DMSP data, its variability is also traced time to time. Figure 10 is an example of this variability in Akita city of Tohoku area although only high gain data are available for a rather long time duration. This result says that light energy loss in this city increases even after crashing the Japanese bubble economy.

Since we can detect such a variability at each city, this method is very good to public awareness of environmental problems. If people in a city make an effort to reduce light pollution and energy loss, its variability is able to be an index of their efforts. Usually, although some people try to make actions in order to solve an environmental problem, they will mostly stop to do so after they realize that problem is still going worse since the majority of people do not take care the problem. However in our case of light energy loss, they can correctly get an idea how much they contribute to reduce light energy loss in their city even if it increases under a global evaluation. Then, they are confident that they are contributing on a global energy and environmental problem. Once they realize their contribution on the problem, they will also start to contribute to the other energy and environmental problems. Therefore, this kind of feed-back between public efforts and those evaluation will create a strong impact to public awareness of a energy problem.

As already mentioned in this paper, our data reduction processes are rather slow because of a shortage of manpower. Even so, we will continue our works understanding the above important contribution. Another difficulties are that the US Air Force accepts only a small fraction of observations with low-gain mode and that a geometrical resolution of the DMSP observations is rather poor (at best 1.2 km x 1.2 km). Therefore, we need a new satellite with high observing flexibility and high resolution.

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