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POTENTIAL AND PERSPECTIVES OF REMOTE SENSING OF THE OCEAN–ATMOSPHERE INTERACTION PARAMETERS

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RESUMEN

En la formación del clima intervienen una serie de procesos muy complejos que interaccionan en el sistema "atmósfera-océano-continentes-criósfera". El problema del clima y sus cambios originados naturalmente y por factores antropogénicos exige el seguimiento de un amplio conjunto de parámetros que caractericen no sólo al clima sino los rasgos propios de la atmósfera, océano, superficie terrestre y cubierta de hielo.

La determinación del conjunto de parámetros requerido debe obtenerse a partir del modelado numérico dirigido a la planeación del sistema global para monitoreo del clima. Las restricciones sobre los datos observacionales son muy variables y fuertemente dependientes del modelo del clima utilizado.

En base a estas consideraciones, se presenta una estimación de los parámetros requeridos que integran el conjunto, se incluye precisión y resolución espacio-temporal. Se analizan las posibilidades de medición por los sistemas actuales, los ya diseñados y los que se desarrollarán en los años ochentas. Finalmente, se evalúan los errores que se cometen utilizando microondas en la determinación de la temperatura de la cubierta de hielo y de la superficie del mar.

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ABSTRACT

In climate formation very complex processes interact in the system "atmosphere-ocean-continents-cryosphere". The problem of climate and its changes naturally and anthropogenically originated demands tracking of a wide set of parameters characterizing not only the climate itself but also the various features of the atmosphere, ocean, land and ice cover.

The criterion for the determination of the required set of parameters should be obtain through numerical modelling aimed at planning the global system for climate monitoring. The restrictions upon the observational data are quite variable and depend strongly on the climate model used.

An estimation based on the above considerations, is presented of the parameters that constitute the required set, precision, temporal and spatial resolution are also included. An analysis is made of the measurement possibilities of the actual systems, of those already designed and those to be developed in the 80's. Finally, an evaluation is presented of the errors committed in the use of microwaves to determine ice cover and sea surface temperatures.

The increasing importance of the problem of climate and its changes precipitated by both natural and anthropogenic factors puts forward the task of monitoring the climate and its variations (Izrael, Yu, A., 1977; Kondratyev, K. Ya., 1971; Suomi, V. E., 1977). The complexity of processes interacting in the system "atmosphere-oceans-continents-cryosphere" that are responsible for climate formation, necessitates tracking a wide set of parameters characterizing not only the climate itself but also the various features of the atmosphere, ocean, land and ice cover (Kondratyev, K. Ya., 1977; Physical basics of climate and its variations, 1977; Smagorindky, J., 1977). In that aspect the monitoring of the ocean-atomosphere interaction parameters acquires key importance.

Naturally, the numerical modeling of climate aimed at planning the global system for climate monitoring should serve as a basis for determining the needed set of parameters. The restrictions upon the observational data are quite variable and depend strongly on the climate model used. The 3-D modeling is obvious to put forth the heaviest of them. For example, M. E. Schlesinger, M. E. (1977) has analyzed some cases by checking the results of numerical climate modeling by means of the University of Oregon 2-layer model of climate against observational data. These cases referred to: (I) parameterization of radiation transfer; (II) modeling the cloud formation processes; (III) reproducing the hydrological cycle; (IV) modeling the snow cover formation processes; (V) description of processes in the oceanic mixing layer; (VI) paleoclimate numerical modeling.

The space observational instrumentation is naturally of decisive importance through it should be stressed that it does not in any way reduce the need to further elaborate the routine techniques (surface, ship-, aircraft-, balloon-borne). In this respect the recommendations worked out by the 1974 Stockholm conference (The physical basis of climate and climate modeling, 1975) and the US plans for satellite climate monitoring (Potential shuttle spacelab applications, 1974) are of particular interest.

NASA has undertaken the planning of a 10-year program for climatic research, its basis being the design and implementation of a system for monitoring the climate parameters. Table 1 presented in (Potential shuttle spacelab applications, 1974) lists the most important of them indicating their comprehensive determination and description. It includes also the complex interactions whose monitoring will not be feasible even in the future.

In this list only those parameters are included which have to be observed from space because they either refer to remote areas (deserts, polar regions, global ocean) or need global coverage.

It is assumed that the measurement errors must not exceed 25% of natural variability for the parameters pertinent to boundary conditions, while accuracy in other cases is expected to be sufficiently high for testing the reliability of theoretical climate models. The complexity of satellite observational systems now existing and being planned makes it possible on the whole to meet such restriction. The demands on the accuracy of determining the climate parameters for separate categories B, C and X are explicitly detailed in Table 2 and 3. Climate of B category is understood as regional with characteristic time scales of more than a month but less than a decade. The principal aim in this case consists in forecasting the variability of regional (characteristic scale of the order of hundreds km) and global climates taking account of the earlier obtained and constantly accumulating observational data.

For climate C the time scales longer than a decade are characteristic. The final aim lies in understanding the cause of the global climate natural variability, while the starting steps are the studies of the factors affecting the radiative balance, the interaction of radiation and cloud formation processes, the heat transfer by oceanic currents, ice cover physics, etc.

Climate X is determined as that affected by man's industrial activities on all the spatial and temporal scales, while the main aim consists in foreseeing the anthropogenic variations of climate in order to adopt corresponding decisions. It should be stressed that the synchronous satellite, aircraft and surface measurements are of particular importance for determining a whole number of parameters (precipitation, oceanic currents, ocean-atmosphere interaction, etc.) whith needed accuracy as far as the remote sensing data itself is not single.

The experience gained in the design and practical application of the space remote sensing techniques up to the present time testifies to wide potential of these techniques. The most significant input has been made through implementing the satellite program aimed at obtaining the meteorological information and data on natural resources (the Cosmos, Meteor, Tyros, Nimbus satellite series and others). The important results of advancing the satellite meteorology consist in solving such problems as the surface temperature determination, retrieving the vertical profiles of temperature, ozone and water vapor, the wind field, tracking the dynamics of the ice and snow covers, sea roughness, studying the Earth radiation balance.

The studies carried out on board manned spacecraft and orbital stations made it possible first of all to accumulate wide experience in interpreting the surface images with the aim of determining different features and characteristics of natural formations. The problems of retrieving the vertical profiles of the optically active minor gas components in the stratosphere from the data of occultation soundings along the sloping tracks have been successfully solved. The use of quantitative characteristics of the horizon atmospheric brightness field proved to be fruitful in determining the atmospheric dust load.

In view of the task of remote sensing of the ocean-atmosphere interaction parameters (sea surface temperature, ice cover, oceanic currents, upwelling, ocean pollution, heat balance, etc.) the design of the microwave remote sensing techniques acquires particular importance. Therefore, we shall deal in short with one of the aspects of remote sensing from space, connected with the use of the microwave range. The microwave range has a number of advantages in comparison with the visible and infrared that are based on certain features of radiative transfer through the atmosphere and the underlying surface radiative characteristics. These include: (i) a considerably weaker attenuation of microwave radiation by atmospheric gas components and hydrometeors; (ii) a large variability range of the different underlying surfaces' radiative properties.

The first feature meakes it possible to quite easily describe the radiative transfer, especially in the longwave part of the spectrum, and to obtain the information on atmosphere and underlying surface through clouds by high-altitude observations. The second enables one to discern separate types of the underlying surface, to evaluate the impact of various physical parameters on the state of the surface. Moreover, as long as the microwave radiation extinction by soil is also considerably lower than in the visible and infrared, an opportunity exists for obtaining information from depths.

Let us deal with the possibilities of determining by means of microwave sounding the ice cover characteristics that are of considerable interest in ocean-atmosphere interaction studies. The most simply and surely determined are the ice cover boundaries and cohesiveness. The immediate value of the radiobrightness temperature registered by a radiometer is determined by the ratio of the ice covered and clear water surfaces. The existence of a linear relationship between the radiobrightness and ice-cover cohesiveness was first experimentally discovered from the aircraft measurement data (Rabinovich, Yu, I., Shchukin, G.G., Novoselov, A. J., 1970). But the later studies during the joint soviet-american Bering sea experiment in particular, have shown this linear dependence to split into a family of lines for ices of different electrophysical properties each line being characteristic for certain ice types. Hence, the accuracy of determining the ice cover cohesiveness significantly depends on the availability of a-priori information on ice type that may be obtained from perennial data, satellite image analysis and so on. We also note that some *a-priori* information on ice cover type can be obtained in the course of spectral measurements of ice microwave emission. Let us evaluate the error in determining the ice cover cohesiveness.

The initial expression for the radiobrightness temperature of the ice-water system can be presented as follows:

$$T_b(P) = T_1 (1 - p) + T_2 p \tag{1}$$

where T_1 is the radiobrightness temperature of clear sea water, T_2 – the ice radiobrightness temperature, p – the ice cover cohesiveness. From this expression the following formula can be easily obtained for the relative error in determining the cohesiveness:

$$\frac{\Delta p}{p} = \Delta T_1 \left[\frac{1}{T_2 - T_1} - \frac{1}{p(T_2 - T_1)} \right] + \Delta T_b \frac{1}{p(T_2 - T_1)} + \Delta T_2 \frac{1}{T_2 - T_1} \tag{2}$$

On the side we make one interesting point. In writing (1) the influence of the atmosphere was not taken into account. It is done so because as has been shown in (Rabinovich, Yu. I., Shchukin, G. G., 1974), the emission coefficient of the underlying surface being high (0.8–0.9), the atmospheric input to microwave emission in the 0.8–3 cm band is insignificant even with high amounts of liquid water and vapor being present in the atmosphere. The ice cover cohesiveness being quite high even in the edge zone, the total emission coefficient of the ice-water system remains within the given bounds.

We proceed now to evaluate the error in determining the cohesiveness. In order to do this, one has to get the values for all the parameters in

(2). First of all let us state some *a-priori* information. We shall treat the problem of determining the cohesiveness for the winter-to-spring season, when the air temperature over ice is about −20° C on the average. The observational wavelenght is 3 cm. In this case the average radio-brightness temperature of compact ice cover will be T_2 = 237K, its possible variations which depend on the ice type not exceeding 15K according to calculations, i.e. ΔT_2 = 15K. The water temperature in the iced zone usually varied from 0 to −4° C, which corresponds to the average radio-brightness temperature of T_1 = 105K, the absolute error being ΔT_1 = 3K. The absolute error of radiobrightness temperature measurement may be assumed to be $\Delta T_B(p)$ = 5K for instrumentation of average sensitivity, allowing for calibration error. As seen from (2), the relative error in determining ice cover cohesiveness depends on cohesiveness itself and for our case varies from 21% to 17% with cohesiveness changing from 0.5 to 1.0. The principal error component is the error due to uncertainty in the ice cover type (the third additive in (2)). Thus feeding additional *a-priori* information on the dominant ice types in the studied area one can significantly diminish the total error in determining the ice cover cohesiveness.

Some comments on the possibility of determining the ice age characteristics. As shown in (Rabinovich, Yu. I., Loshilov, V. S., Shulgina, E. M., 1975), the radiobrightness temperatures of the different sea ice types scarcely differ at any wavelenghts. This is associated with weak differences in the electrophysical properties (dielectric constants) of various ice types. The main possibility of determining the ice age characteristics probably lies in the appearance of noticeable scattering from perennial ices explained by their structural inhomogeneity. This scattering leads to appearance of particularities in the Perennial ice microwave emission spectral course in comparison with that of one-year ice. Apart from that some data on the ice cover thickness for the ice thinner than 1 m can be acquired through analyzing the microwave emission at wavelenghts above 15 cm. In this range there can be observed an anomalous increase in the radiobrightness temperature due to shine-through of the water base. However even theoretical estimates of the error in determining the ice age characteristics appear impossible as far as calculations made according to models suggested in (Tsang, L., Kong, J. A., 1975) show significant differences from the experiment. Both theoretical treatises and special aircraft studies simultaneous with the ground-based measurements of the ice electrophysical properties must be made in order to finally solve this problem.

Now let us proceed to the possibility of determining the sea surface temperature from microwave measurements. The microwave sea surface temperature measurements have the advantage of being weather independent. But, as has been shown in (Shifrin, K. S., Rabinovich, Yu. I., Shchukin, G. G., 1963), the accuracy of inversing the radiation to temperature is 5 times lower in the centimeter range than in the infrared. In order to evaluate the error in measuring the sea surface temperature with the allowance for atmospheric influence, we'll use the solution of the radiation transfer equation under the approximation of pure absorption:

$$T_b = \epsilon T_o e^{-\tau} + T_o^{*}(1 - e^{-\tau}) + T_o^{**}(1-\epsilon)(1 - e^{-\tau})e^{-\tau} \qquad (3)$$

In this expression:
T_o^* and T_o^{**} are the effective atmospheric temperatures for the down—and upward radiation, respectively: ϵ — the emission coefficient: τ — the optical thickness of all the absorbing components.

In first approximation: $T_o^* = T_o^{**} = T_o - \Delta T$, where ΔT is the wavelength-dependent adjustment to temperature at the surface. It has been calculated in (Eliseev, G. V., Stepanenko, V. D., 1976) on the basis of the statistical data of the aerological sounding of the atmosphere, and also by use of the McClatchey atmospheric models (McClatchey, R. A., 1970).

The rms error in determing the sea surface temperature σT_o is given by the expression

$$\sigma^2_{T_o} = \left(\frac{\partial T_o}{\partial T}\right)^2 \sigma^2_{\tau} + \left(\frac{\partial T_o}{\partial \epsilon}\right)^2 \sigma^2_{\epsilon} + \left(\frac{\partial T_o}{\partial T_o^*}\right)^2 \sigma^2_{T_o^*} + \left(\frac{\partial T_o}{\partial T_b}\right)^2 \sigma^2_{T_b} \qquad (4)$$

taking into account the given accuracy of all the parameters of influence. The rms errors σ_i of determining all the influencing parameters enter this equation together with the error of the radiobrightness temperature measurement.

The values of partial derivatives can be obtained from Equation (3):

$$\frac{\partial T_o}{\partial \tau} = \frac{T_b - T_o^*}{\epsilon e^{-\tau}} - \frac{1-\epsilon}{\epsilon} T_o^* e^{-t}$$

$$\frac{\partial T_o}{\partial T_o^*} = -\frac{1-e^{-\tau}}{\epsilon e^{-\tau}} - \frac{1-\epsilon}{\epsilon}(1-e^{-\tau})$$

$$\frac{\partial T_o}{\partial T_b} = \frac{1}{\epsilon e^{-\tau}}$$

$$\frac{\partial T_o}{\partial \epsilon} = \frac{-T_b + T_o^*(1-e^{-\tau}) + T_o^*(1-e^{-\tau})e^{-\tau}}{\epsilon^2 e^{-\tau}} \tag{5}$$

To reduce the notation, the dependence on wavelenght is not shown here, although is must be kept in mind that all these parameters depend on λ. In order to estimate the influence of different parameters the calculations were made for the mean latitudes summer-time model according to (Tsang, L., Kong, J. A., 1975). This model is characterized by the atmospheric temperature $T_o = 294K$, total water vapor amount 30 kg/m^2 and the liquid water content 0.25 kg/m^2. Let us set the error vector for all the parameters in (4):

$$\sigma_\tau = 0{,}0002;\ \sigma_{T_o^*} = 5K,\ \sigma_\epsilon = 0{,}002;\ \sigma_{T_\epsilon} = 0{,}5K$$

The assumed absolute error values are not overestimated, but on the contrary are slightly less than those actually reachable now.

The calculation results have shown that the absolute error in determining the sea surface temperature in the wavelenght range 4.5– 8.5 cm constitutes 2.1K which, of course, is considerably higher than the accuracy limits set above.

If one estimates the error generated by the atmospheric influence and instrumental measurement errors alone ($\sigma_\epsilon = 0$), the absolute error for even such a case is about 1.5K for $\sigma_{T_B} = 0.5$K and about 0.7K for $\sigma_{T_B} = 0.2$K.

Thus, the accuracy of the absolute measurements of the water surface temperature in the microwave range is not too high and the only way of improving it probably lies in using the groundtruth measurement data from buoys and ships.

We have illustrated the capabilities of microwave remote sensing by two examples referring to determination of the two most important characteristics of the ocean-atmosphere interaction: the ice cover and the sea surface temperature. Naturally: (i) the microwave range potential is much wider; (ii) the optical range should be paid serious attention to apart from the microwave one. In this last case the account of the atmosphere's reduction function and elimination of the influence of clouds (when cloudiness is not the object of studies) acquire primary importance.

TABLE 1

The State and Perspectives of Monitoring the Climate Parameters from Space.

Parameter	Can the demands to parameter determination be met by		
	Present systems	Designed systems	Systems of 80's
1	2	3	4
Weather parameters			
1. Temperature profile		yes	yes
2. Surface pressure	No remote sensing technique available		
3. Wind speed	Standard meteorol. observat.	By watching cloud movement.	
4. Sea surface temperature		yes	yes

(to be continued)

Table 1 (continued)

1	2	3	4
5. Air humidity		yes	yes
6. Precipitation		yes	yes
7. Cloud cover		yes	yes
8. Boundary layer stability		-	-
Ocean parameters			
4a. Sea surface temperature	no	yes	yes
9. Evaporation	no	no	no
10. Tangential wind tension	no	no	no
11. Turbulent exchange with atmosphere	no	no	ho
12. Ocean surface topography	no	possible	possible
13. Heat store of the ocean upper layer	no	no	no
14. Temperature profile	partially	partially	partially
15. Speed profile	partially	partially	partially
Radiation balance			
7a. Cloudiness (modulation of radiation)	almost	yes	yes
16. Components of regional radiation balance	no	yes	yes
17. Equator-pole gradient	no	no	yes
18. Surface albedo	yes	yes	yes

(to be continued)

Table 1 (continued)

1	2	3	4
Atmosphere composition			
21a. Solar ultraviolet radiation	no	yes	yes
33. Stratospheric aerosol depth	no	almost	almost
34. Tropospheric aerosol depth	no	no	no
35. Ozone	no	yes	yes
36. Stratospheric water vapor	no	yes	yes
37. Nitrous oxide and nitric oxides	yes	yes	yes
38. Carbon dioxide	yes	yes	yes
39. Fluorocarbons	yes	yes	yes
40. Methane	yes	yes	yes

Table 1 (continued)

1	2	3	4
19. Surface radiation balance	partially	partially	partially
20. Solar constant	no	yes	yes
21. Solar ultraviolet radiation	no	yes	yes
<u>Ground hydrology, vegetation</u>			
6a. Precipitation	no	no	no
18a. Surface albedo	yes	yes	yes
22. Surface layer humidity	no	partially	yes
23. Soil humidity (root zone)	no	no	no
24. Vegetation cover (forests excluded)	almost	yes	yes
25. Evapotranspiration	no	no	no
26. Moisture store	no	no	no
<u>Cryosphere parameters</u>			
27. Sea ice (open water percentage)	yes	yes	yes
28. Snow cover (total area percentage)	yes	yes	yes
29. Snow water content	no	yes	yes
30. Ice cover topography	no	probably	yes
31. Ice horizontal drift speed	yes	yes	yes
32. Ice cover boundaries	yes	yes	yes

(to be continued)

TABLE 2 Demands on the [illegible] climate parameters' accuracy

Principal groups of climate parameters	Parameters	Needed accuracy	Allowed accuracy	Horizontal resolution km	Temporal resolution
1	2	3	4	5	6
Principal meteorological elements according to GARP	Temperature profile	1°C	2°C	500	12-24 hrs
	Surface pressure	1 mb	3 mb	500	12-24 hrs
	Wind speed	3 m/s	3 m/s	500	12-24 hrs
	Sea surface temperature	0.2°C	1°C	500	3 days
	Humidity	7%	30%	500	12-24 hrs
	Precipitation	10%	25%	500	12-24 hrs
	Cloudiness:				
	a) amount	5%	20%	100	
	b) top temperature	2°C	4°C		
	c) albedo	0.02	0.04		
	d) total water amount	10mg/cm^2	50 mg/cm^2		

(to be continued)

Table 2 (continued)

1	2	3	4	5	6
	Surface temperature	0.2°C	1°C	500	1 month
Ocean	Evaporation	10%	25%	500	1 month
parameters	Turbulent heat exchange	10 Wt/m^2	25 Wt/m^2	500	1 month
	Tangential tension	0.1 dyn/cm^2	0.3 dyn/cm^2	500	1 month
	Cloudiness (radiation modulation):				
	a) amount	5%	20%		
	b) top temperature	2°C	4°C		
	c) albedo	0.02	0,04		
Radiation balance	d) total water amount	10 mg/cm^2	50 mg/cm^2		
	Regional radiation balance components	10 Wt/m^2	25 Wt/m^2	500	1 month
	Equator-pole gradient	2 Wt/m^2	4 Wt/m^2	1000	1 month
	Surface albedo	0.02	0.04	50	1 month
	Surface radiation balance	10 Wt/m^2	25 Wt/m^2	500	1 month
	Solar constant	1.5 Wt/m^2	1.5 Wt/m^2	-	1 day
	Solar u.v. radiation	10% for 50A band	-	-	1 day

(to be continued)

Table 2 (continued)

1	2	3	4	5	6
Ground hydrology and vegetation cover	Precipitation	10%	25%	500	1 month
	Surface albedo	0.02	0.04	500	1 month
	Ground humidity	0.05 g/cm^3 of soil	4 levels	500	1 month
	Soil humidity in the root zone	0.05 g/cm^3	4 levels	500	1 month
	Vegetation coverage	5%	5%	500	1 month
	Evapotranspiration	10%	25%	500	1 month
	Vegetation moisture supply	4 levels/ 2 levels		500	1 month
Cryospheric parameters	Sea ice (open water percentage)	3%	3%	50	3 days
	Snow (cover percentage)	5%	5%	50	1 week
	Snow (water content)	1 cm	3 cm	50	1 week

TABLE 3 Demands on Climates C and X parameters accuracy (only parameters additional to those in Table 2 are given)

Principal groups of climate parameters	Paramcter	Needed accuracy	Allowed accuracy	Horizontal resolution km	Temporal resolution
1	2	3	4	5	6
Ocean parameters	Ocean surface elevation	1 cm	10 cm	variable	1 week
	Heat store of the oceanic upper layer	1 Kcal/cm^2	5 Kcal/cm^2	500	1 month
	Temperature profile	0.2°C	1.0°C	variable	1 month
	Speed profile	2 cm/s at the surface	10 cm/s	variable	1 month
		0.2 cm/s at depths	1 cm/s	variable	1 year
Cryospheric parameters	Ice cover elevation	10 cm	1 m	Point targets	1 year
	Ice cover drift	50 m/year	100 m/year	1-3 km	1 year
	Ice boundaries	1 km	5 km	-	1 day

(to be continued)

Table 3 (continued)

1	2	3	4	5	6
Atmospheric composition	Solar u.v. radiation	10% for 50Å	-	-	1 day
	Stratospheric aerosol optical thickness	0.002	0.01	250 km (N-S)	1 month
	Tropospheric aerosol optical thickness			1000 km (E-W)	
	Ozone	0.005	0.02	500	1 month
		0.005 cm	0.02 cm (total content) 10% at effective altitude	250 km (N-S) 1000 km (E-W)	1 month
	Stratospheric water vapor	0.05 ppm	0.05 ppm	250 km (N-S) 1000 km (E-W)	1 month
Tropospheric composition	Nitrous oxide	0.01 ppm	0.03 ppm	-	1 year
	Carbon dioxide	0.5 ppm	10 ppm	-	1 year
	Fluorocarbons	0.03 ppm	0.1 ppm	-	1 year
	Methane	0.05 ppm	0.15 ppm	-	1 year

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