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Ocean heat content and Earth’s radiation imbalance

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ABSTRACT

Earth’s radiation imbalance is determined from ocean heat content data and compared with results of direct measurements. Distinct time intervals of alternating positive and negative values are found: 1960–mid-1970s (−0.15), mid-1970s–2000 (+0.15), 2001–present (−0.2 W/m^2), and are consistent with prior reports. These climate shifts limit climate predictability.

1. Introduction

A strong connection between Earth’s radiative imbalance and the heat content of the oceans has been known for some time (see, *e.g.*, Peixoto and Oort [1]). The heat content has played an important role in recent discussions of climate change, and Pielke [2] has revived interest in its relationship with radiation. Many previous papers have emphasized the importance of heat content of the ocean, particularly the upper ocean, as a diagnostic for changes in the climate system [3–7]. In this work we analyze recent heat content data sets, compare them with corresponding data on radiative imbalance, and point out certain irregularities that can be associated with climate shifts.

In Section 2 the conservation of energy is applied to the climate system and the approximations involved in making the radiation-heat content connection are discussed. In Section 3 data sources are enumerated. Section 4 gives the radiation imbalance for the earth’s climate system. In Section 5, climate shifts, radiative imbalances and other climate parameters are discussed. A summary is in Section 6.

2. Energetics of the climate system (CS) of the earth

Earth’s climate system lies between two concentric spheres, an outer one that surrounds the whole system at an altitude of 20 km and an inner one that is beneath the deepest ocean (11 km). It may be divided into four broadly homogeneous components, the atmosphere, the land and shelves, the upper ocean, of depth ∼700 m, and the deep ocean, shown schematically in Fig. S-1. (Figures and tables in the Supplementary material are designated S-1, S-2, etc.)

Since the areas of the two concentric spheres are negligibly different from that of Earth, A_{Earth}, and since the overwhelming majority of the relevant thermal energy of the CS is within the upper ocean (O) [2,3,8–10], we use conservation of energy to write

$$F_{\mathrm{TOA}}(t) + F_g = \frac{1}{A_{\mathrm{Earth}}}\frac{dH_{\mathrm{O}}}{dt}\ \mathrm{W/m^2}, \tag{1}$$

where F_{TOA} is the net inward radiative flux through the outer sphere, F_g is the average inward geothermal flux [11–13] through the inner sphere, and H_{O} is the thermal energy of the upper ocean. Numerous assumptions underlie this equation, particularly the neglect of the thermal energy of the other components of the CS (atmosphere, land, and deeper ocean). They are discussed in the Supplementary material.

The geothermal contribution is constant, but cannot be ignored because it contributes directly. The flux into the ocean and trenches averages 101 ± 2.2 mW/m^2 and that into the land and shelves averages 65 ± 1.6 mW/m^2 (globally averaged, 87 ± 2.0 mW/m^2) [11]. Some fraction of the entire 87 mW/m^2, called F_g, contributes to dH_{O}/dt. The land and shelves component, measured at the surface, heats the atmosphere and is disposed of the same way as the radiative input is (some out the top as part of F_{rad}, some to O). The ocean floor component, measured at the

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ocean floor, heats both O and O′ (the deeper ocean). It is possible, therefore, that as little as 30 mW/m^2 contributes to O. Except where noted, we use the larger value here.

In the literature one generally finds the total ocean heat content expressed in units of 10^{22} J = 10 ZJ and time scales in years. When dH_O/dt is evaluated in these units, we have, in W/m^2,

$$F_{TOA}(t) = 0.62\frac{dH_O}{dt} - F_g. \qquad (2)$$

3. Sources of data and methods

3.1. Ocean heat content

The globally averaged heat content H_O is integrated over the upper layer of the ocean. Pielke [12] mentions 3 km as sufficient depth of the layer. The data of Domingues et al. [14] and Domingues [15] (hereinafter D08) and Levitus et al. [16] go to 700 m. It is assumed that measuring the heat content to a depth of 700 m is adequate to determine trend values. Measurements of annual values of H_O have been reported by Willis et al. [17] and by Levitus et al. [16,18]. They use several million historical worldwide ocean temperature-*vs*-depth profiles. More recent determination of annual values (and uncertainties) of H_O are given by D08 over the range 1950 to 2003 and by Willis et al. [13] and Willis [19] (hereinafter W08) over the range July 2003 to June 2008. D08 values are listed in Table S-1.

A new system was deployed in 2000 consisting in part of a broad-scale global array of temperature/salinity profiling floats, known as Argo [20]. Monthly values of Argo H_O were determined from data to a depth of 750 m. Values from July 2003 to January 2008 are given by W08 and are listed in Table S-1.

3.2. Net incoming radiation flux: F_{TOA}

The satellite system known as the Clouds and the Earth's Radiant Energy System (CERES) measures long wave (LW) and short wave (SW) radiation coming from the earth [16,21]. From this data one can determine the net radiation at the "top-of-the-atmosphere" (TOA), F_{TOA}. These quantities can be determined with good relative precision (less than 0.6 W/m^2 [22]). However, systematic uncertainties in F_{TOA} are estimated by Loeb to be $2\sigma = 4.2$ W/m^2. To circumvent the systematic uncertainties, Wong et al. [23] adjusted the inter-annual variability of F_{TOA} from CERES data to be the same as the F_{TOA} value from ocean heat content data during the overlapping time interval. In this Letter because of the large systematic uncertainties we adjust the CERES mean to that of the ocean data.

Monthly global values of F_{TOA} from March 2000 to October 2005 have been provided to us by Wong [24]. These values are listed in Table S-1 and will be referred to as "CERES data."

3.3. Flux from the interior of the earth

Pollack et al. [11] studied 24,774 heat flow measurements at 20,201 worldwide sites. They determined a global mean heat flux of 87 ± 2.0 mW/m^2 (see discussion in Section 2).

3.4. Solar flux

The mean solar flux S_0 at the earth's orbit is assumed to be 340 W/m^2 (uncertainty of ±1 W/m^2) [22]. Because of the eccentricity ε(value = 0.0167) of the earth's orbit the actual solar flux has a time dependence

$$S(t) \approx S_0\left[1 + 2\varepsilon\cos(2\pi t/T)\right], \qquad (3)$$

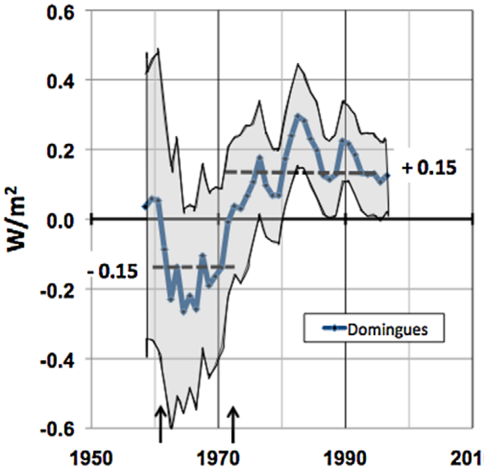

Fig. 1. Top-of-atmosphere radiation flux imbalance F_{TOA} implied by the Domingues heat content data. The arrows indicate dates of climate regime changes. These data are annual values, so no solar eccentricity effect is seen.

where $T = 1$ yr, leading to a peak-to-peak variation of $4\varepsilon S_0 = 22.7$ W/m^2. The response to this annual solar forcing is seen in the monthly CERES and Argo data but not in the D08 H_O data because the latter are averaged annual values.

Consider a pure sinusoid of amplitude A. The peak-to peak amplitude A_{PP} is related to the standard deviation (SD) by

$$A_{PP} = 2 \cdot \sqrt{2} \cdot \mathrm{SD} = 2A. \qquad (4)$$

Both the CERES and the Argo data contain an annual signal along with background and noise. The A_{PP} value of the annual signal in the CERES and Argo data will be independent of the mean or adjustments in the mean. The definition of A_{PP} in Eq. (4) will be used below, where the entire data series is used in the calculation of SD.

4. Analysis of data

4.1. Domingues data (1955 to 2003)

The heat content data H_O in Table S-1 was smoothed (following D08) by a three-year running mean filter to reduce the noise. The value of the implied radiation imbalance, F_{TOA}, was estimated in the following way. The slope of H_O with time for each year was calculated by the difference of value of H_O at $n/2$ years forward and the value of H_O at $n/2$ years backward, divided by n. The value of n should be larger than any short coherence times so that the two values of H_O are statistically independent. The results are nearly independent of n when $n > 10$ years; $n = 16$ was used. There is a loss of $n/2$ years of data at each end of the data series. The uncertainty in dH_O/dt was estimated by adding the uncertainties of the two H_O values in quadrature. The entire geothermal flux $F_g = 0.087$ W/m^2 was subtracted from dH_O/dt to obtain F_{TOA} (Eq. (4)). A plot of the implied F_{TOA} is shown in Fig. 1. The flux imbalance is seen to be negative between 1960 and the mid-1970s with an average value of -0.15 ± 0.11 W/m^2. In the mid-1970s the sign changes from negative to positive and from then to 1995 the flux imbalance has the value $+0.15 \pm 0.07$ W/m^2.

4.2. Argo data (July 2003 to June 2008)

The quantity $0.62\,dH_O/dt$ [see discussion of units at Eq. (2)] was calculated for each date, using seven points, resulting in the loss of three months data at each end of the data series. Eq. (4) was again used to obtain the implied F_{TOA}, plotted in Fig. 2. The effect of the eccentricity of the earth's orbit is quite prominent.

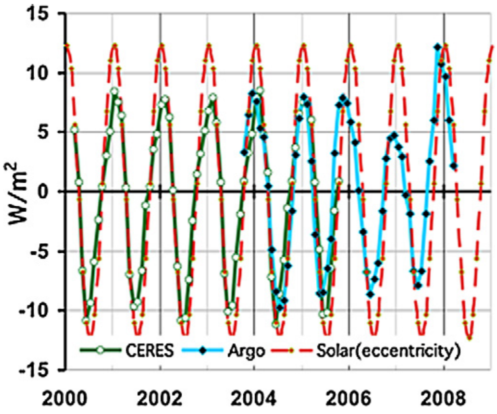

Fig. 2. Top-of-atmosphere radiation flux imbalance F_{TOA} implied by the Argo heat content data (blue) and from the radiation measurements by CERES (green). Since these data have monthly resolution, the annual solar eccentricity effect in irradiance (dashed red) can be compared.

The change of amplitude in the last two cycles is not understood but is reflected in the size of the assigned error bars.

Average F_{TOA}: 12-month symmetric averages were calculated for each date. Then an average of these was determined to be -0.244 ± 0.990 W/m^2 ($\pm$ are the 1-sigma values). The large uncertainty is due to the large amplitude changes in the last cycle. The period July 2003 to October 2005 overlaps the CERES record. The CERES data was shifted so that its average in this period coincided with the Argo average, as discussed below.

Trend of average: The slope of the values of the 12-month symmetric averages was found to be close to zero but quite dependent on the choice of end values

A_{PP} *values*: 12-month symmetric averages of A_{PP} were calculated for each date. Then an average of these was determined to be 17.3 ± 2.1 W/m^2.

Trend of A_{PP} *values*: The slope of the 12-month symmetric averages of PP values were found for each date. Then an average of these was determined to be -1.06 ± 3.19 (W/m^2)/yr.

Uncertainties in F_{TOA} from atmosphere and from ocean below 750 m will change the average but not A_{PP} values. The value of A_{PP} was found to depend on the number n of months used in computing the slope ($n = 5$ gave a value 10% larger than that for $n = 7$).

4.3. Levitus et al. data (2009)

In the most recent determination of OHC, Levitus et al. [18] report that for 1969–2003 "... the linear trend ($0.32 \pm 0.05 \times 10^{22}$ J yr^{-1}) in ocean heat content remain similar to our earlier estimate." This converts to $0.62 \times (0.32 \pm 0.05) = 0.198 \pm 0.03$ W/m^2. They also report "After 2003, OHC700 increases to a plateau during 2004–2007." This will be interpreted as $0.62\, dH_O/dt \approx 0$. Therefore, from Eq. (2), we have $F_{TOA} = -F_g = -0.087 \pm 0.05$ W/m^2.

4.4. CERES data (2000–2005)

These data determine F_{TOA} directly.

Average: The CERES-derived F_{TOA} values have good instrumental stability (less than 0.4 W/m^2), but large systematic uncertainty ($2\sigma = 4.2$ W/m^2) [22]. We followed Wong and Wielicki [25] and adjusted the mean this data set to the mean of the Argo F_{TOA} during the overlapping period (July 2003 to October 2005). This meant subtracting 1.23 from the CERES data values listed in Table S-1. No other adjustments or modifications were made to the CERES data. After doing this, 12-month symmetric averages were calculated for each date. Then an average of these was determined to be -0.303 ± 0.187 W/m^2.

Trend of average: The slope of the values of the 12-month symmetric averages was found to be -0.485 (W/m^2)/yr.

A_{PP} *values*: 12-month symmetric averages of A_{PP} were calculated for each date. Then an average of these was determined to be 18.7 ± 0.7 W/m^2.

Slope of A_{PP} *values*: The slope of the 12-month symmetric averages of the A_{PP} values were found for each date. An average of these was determined to be -0.016 ± 0.862 (W/m^2)/yr.

Uncertainties: S_0 will change the average by the same amount. The A_{PP} value will change by $4\varepsilon\Delta S_0 \sim \pm 0.07$ W/m^2.

Table S-2 contains a summary of these various values.

5. Discussion

5.1. The TOA annual effect

That the observed peak-to-peak CERES response of 18.7 ± 0.7 W/m^2 and the Argo peak-to-peak response of 17.3 ± 2.1 W/m^2 are equal within the uncertainties, and that they are nearly in phase with each other, lead us to these tentative conclusions: (1) there is no significant time delay between the annual-scale forcing and deposition of energy in the ocean, and (2) the magnitude of the effect, comparing it with the expected total peak-to-peak input of 22.7 W/m^2, reflects the fact [2] that 90% of the energy is accounted for in the ocean data.

The similarity in magnitude and phase between F_{TOA} and the incoming solar radiation is at first rather surprising. One naively expects a cancellation because of "balancing" with outgoing long-wave radiation (OLR) and the reflected solar. Various factors are involved. There is a roughly six-month phase shift between peaks of OLR and net solar, meaning that the effects add when OLR is subtracted; there is also a phase shift between incoming and net solar because of annual albedo variations. Both of these factors can be seen clearly in the earlier satellite data [1, pp. 120–121].

5.2. Radiation imbalance: F_{TOA}

1960 to 1975. We report an average $F_{TOA} = -0.15 \pm 0.10$ W/m^2 for this period, as inferred from data on H_O.

1975 to 2000. A number of studies for the period prior to 2003 estimated radiative imbalances F_{TOA} (without a subtraction for heat from the interior of the earth) that are close in value. Levitus et al. [16] found 0.20 W/m^2 for 1955 to 1998. Domingues et al. [14] found 0.23 ± 0.04 W/m^2 for the period 1961 to 2003. The IPCC [9, p. 387] give 0.21 ± 0.04 W/m^2. These various numbers span the range 0.20 W/m^2 to 0.24 W/m^2; when corrected for heat from the interior the range is 0.11 to 0.15 W/m^2, which is close to 0.15 ± 0.07 W/m^2 found in this Letter. If the smaller value $F_g = 0.030$ W/m^2 is used (see discussion in the Supplementary material), the range is 0.17 to 0.21, which is still in range. These values are summarized in Table S-3.

After 2000. We have three estimates. The average radiative imbalance F_{TOA} is -0.303 ± 0.187 for CERES and for Argo the implied value is -0.224 ± 0.99 W/m^2. The Levitus et al. [18] value from Section 4.3 is -0.087 W/m^2. Loehle [26] has also analyzed the Argo data (only through January 2008). He reports a trend of $-0.35 \pm 0.2 \times 10^{22}$ J/year, which is an equivalent flux of -0.22 ± 0.3 W/m^2. Again applying F_g, the flux at TOA is adjusted to -0.31.

In sum, we find three distinct time intervals of alternating positive and negative F_{TOA}, which are: 1960 to mid 1970s, mid 1970s to 2000, and 2001 to present. The respective mean F_{TOA} fluxes are: -0.15 ± 0.07, $+0.15 \pm 0.10$, and -0.2 to -0.3 W/m^2. See Fig. 3.

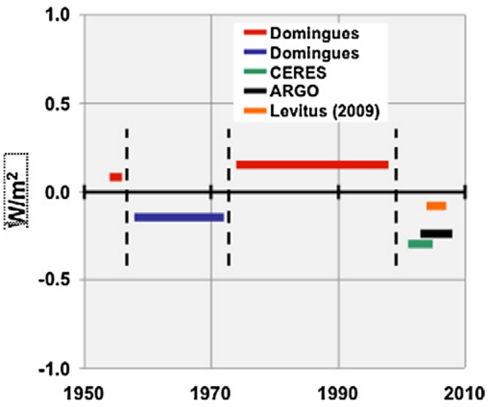

Fig. 3. Implied average F_{TOA} in selected periods showing the relationship to climate shifts (dashed lines). 1960 to 1975: -0.15 ± 0.10 W/m^2; 1975 to 2000: 0.15 ± 0.07 W/m^2; and after 2000: -0.303 ± 0.187 for CERES; -0.224 ± 0.99 W/m for Argo; -0.087 ± 0.03 W/m^2 from Levitus [18]. Each of these numbers is changed by $+0.060$ W/m^2 if a more conservative value of F_{g} is used (see Section 5.2).

5.3. Response time

The global energy balance approach of this Letter attempts to account for all of the energy of the climate system on an annual to decadal basis. Data uncertainties and the lack of deepest-ocean data prevent an assessment of long-term heat storage. The time delay between the variations in the flux F_{TOA} and the changes in the ocean heat content appears to be zero, or at most 1 month. That the time of the maximum of annual variation of the measured (CERES) flux and that of the inferred (Argo) flux agree confirms this. There are of course time delays of heat exchanges between elements of the climate system, but these are not relevant as long as H_{O}, the upper ocean heat, is a proper proxy for the total heat content.

As discussed in the Supplementary material, much (49%) of the unreflected incoming solar flux heats the land and atmosphere. The observed lack of time delay between the solar signal and the rate of change of H_{O} implies that this energy either shows up rapidly in the ocean or exits as long-wave radiation and is thereby accounted for as part of F_{TOA}. Here "rapidly" refers to processes occurring on a monthly, or shorter, time scale.

5.4. Relation to "warming commitment"

Wetherald et al. [27] have discussed the concept of "warming commitment," which is defined as the temperature rise that would occur if climate forcing were held constant at its current level. Hansen et al. [28] refer to this concept as an effect "in the pipeline." They compute a value $F_{\mathrm{TOA}} = 0.85$ W/m^2 and use it as a climate forcing to project a future temperature rise. We make a connection with their treatment as follows.

A climate forcing ΔF is a calculated equivalent net radiative flux that would produce the same result as a given climate perturbation with the surface temperature held fixed [29,30]. Forcing is brought into the heat content discussion in many publications (see, *e.g.*, [31,32]). In our notation and under our assumptions,

$$\frac{1}{A_{\mathrm{Earth}}}\frac{dH_{\mathrm{O}}}{dt} = \Delta F - \frac{\Delta T}{\lambda}, \tag{5}$$

where λ is an assumed climate sensitivity. (Climate models have generally found such a linear relationship between ΔF and the surface temperature anomaly ΔT under conditions of zero ocean heating.) Neither ΔF nor λ is determined from observations. Using Eqs. (1) and (5) and ignoring F_{g}, we may write

$$\Delta F = F_{\mathrm{TOA}} + \frac{\Delta T}{\lambda}. \tag{6}$$

Thinking of ΔF as "total forcing" and $\Delta T/\lambda$ as "forcing already responded to," one may call F_{TOA} "forcing not yet responded to." In this way we may understand Hansen's "Of the 1.8 W/m^2 forcing, 0.85 W/m^2 remains." Here 1.8 W/m^2 refers to the net 1880–2003 forcing considering all sources [28]. Next, using a climate sensitivity 0.67 C/(W/m^2), the authors arrive at the "temperature in the pipeline," $0.85 \times 0.67 = 0.6$ C. The theoretical value of F_{TOA} used in this "pipeline" estimate is in conflict with the results of this Letter. For the period prior to 2003, it is 3.5 times the value 0.24. Furthermore, the theoretical values are always (except for volcanic eruptions) positive during the periods in which we have shown clearly negative values. One may therefore question whether any "climate is in the pipeline."

Considering the error bars and several small uncertainties discussed earlier, we cannot entirely rule out some slow leakage of heat into the deeper ocean, which might be considered "in the pipeline." However, the analysis shows that such heat flux would be small compared with that which is currently believed (on the basis of theory) to be transferred.

5.5. Climate shifts

As discussed in Section 4.2 above, F_{TOA} has changed sign three times: early 1960s, early 1970s, and early 2000s. The rapid changes in magnitude at these dates suggest that a climate shift has taken place.

Early 1960s. In Fig. 1 one sees a rapid change of about 0.2 W/m^2 in F_{TOA}, from positive to negative.

Early 1970s. This shift is well documented. A "climate shift" in the mid-1970s has been observed in a variety of climate parameters [33–41]. This climate shift is seen in the F_{TOA} plot of Fig. 1 as a rapid change from negative to positive in the early 1970s of about 0.3 W/m^2.

Early 2000s. The plot in Fig. 3 shows negative values of F_{TOA} since about 2001. Combined with the positive values prior to this date, this gives a shift in F_{TOA} of about 0.4 W/m^2. Cummins et al. [39] have proposed an upper ocean climate index based upon sea surface height data from satellite altimetry and other data which show the mid-1970s climate shift from negative to positive and a later change from positive to negative around 1998 which they call a "shift." Others [37,40,42] also refer to a "shift" in a climate parameter during 1999 to 2002.

The climate shifts as reported in this Letter and observed in numerous climate parameters discussed above indicate a regime change in the earth's climate system. This study suggests that the change in sign of the net radiation flux as inferred from the ocean heat content data is the signature of a climate change from one regime to another.

Tsonis et al. [41], in a study of synchronization in a network of observational climate indices, report a change in the synchronous state during the 1970s, which they identify with a climate shift. In a later paper Swanson and Tsonis [43] find five synchronizations at dates near 1912–1918, 1938–1943, 1958–1961, 1976–1980 and 2001–2002 although they appear not to believe the third one. The results of this Letter support all of the last three.

It is difficult to describe these "climate shifts" using the unbalanced radiation concept. It seems more likely that these climate shifts are associated with changes in climate normal modes involving the ocean currents as Tsonis et al. propose. For example, the El Niño/La Niña phenomena can be described as changes of the climate involving ocean currents. For this case, White et al. [44] state: "... [g]lobal warming and cooling ... arise from fluctuations in the global hydrological balance, not the global radiation balance."

What is the cause of these climate shifts? We suggest that the low frequency component of the Pacific Decade Oscillation (PDO) may be involved. The PDO index changes from positive to negative near 1960; it remains negative until the mid-1970s where it becomes positive; then it becomes negative again at about 2000. This mimics the F_{TOA} data. The PDO index is one of the inputs in the synchronization analysis of Swanson and Tsonis [43].

One would like to be able to predict future climate. Such predictions are based upon the present initial conditions and some expectation that changes in the climate state are continuous. However, if there are abrupt changes such as reported by Swanson and Tsonis then this is not possible. These abrupt changes presumably occur because the existing state is no longer stable and there is a transition to a new stable state.

6. Summary

We determine Earth's radiation imbalance by analyzing three recent independent observational ocean heat content determinations for the period 1950 to 2008 and compare the results with direct measurements by satellites. A large annual term is found in both the implied radiation imbalance and the direct measurements. Its magnitude and phase confirm earlier observations that delivery of the energy to the ocean is rapid, thus eliminating the possibility of long time constants associated with the bulk of the heat transferred.

Longer-term averages of the observed imbalance are not only many-fold smaller than theoretically derived values, but also oscillate in sign. These facts are not found among the theoretical predictions.

Three distinct time intervals of alternating positive and negative imbalance are found: 1960 to the mid 1970s, the mid 1970s to 2000 and 2001 to present. The respective mean values of radiation imbalance in $\mathrm{W/m^2}$ are -0.15, $+0.15$, and -0.2 to -0.3. These observations are consistent with the occurrence of climate shifts at 1960, the mid-1970s, and early 2001 identified by Swanson and Tsonis.

Knowledge of the complex atmospheric-ocean physical processes is not involved or required in making these findings. Global surface temperatures as a function of time are also not required to be known.

Supplementary material

The online version of this Letter contains additional supplementary material. Please visit DOI: 10.1016/j.physleta.2009.07.023.

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