Comments of O. Hellmuth on

"TEOS-10 and the Climatic Relevance of Ocean-Atmosphere Interaction"

by Rainer Feistel

(https://doi.org/10.5194/egusphere-2024-1243, Preprint)

The author of the paper is member of a very productive and powerful community which established a new international seawater standard, called TEOS-10. As can be seen from the reference list of this study, the author itself serves as the leading author of many of the TEOS-10 relevant papers and can be considered as the main driver of this development. The adoption TEOS-10 by the responsible international authorities is a result of intensive scientific research over a period of more than a decade (starting in 2004) including its technical implementation according to the high-quality evaluation standards of IAPWS. TEOS-10 can be considered as a real gem of both oceanographic and atmospheric thermodynamics.

Based on a review of present challenges in the description of ocean-atmosphere interactions the author identified a number of unresolved open questions to which TEOS-10 can provide an important contribution.

Of top priority for the fate of Earth's climate is the diagnosis of a hitherto unexplained ocean warming rate that is equivalent to an excess heat flux of about 1.3 W m^{-2}. The key problem in the elucidation of the physical reason for this excess heat flux is of metrological origin: for the time being the uncertainties (noise) in the heat flux estimation is by at least one order of magnitude larger than the physical signal. Therefore, root-cause analysis based on empirical data must be replaced by model-based deductions. This cumbersome situation will hold on until the required degree of metrolocigal certainty in the heat flux determination is achieved. Based on my own examinations of the authors considerations on the role of the relative humidity (RH) in the marine surface layer, I confirm authors estimation that a tiny increase in RH of only 0.2 %rh might be suffice to reduce the ocean evaporation by the observed 1.3 W m^{-2} and, as a consequence, to increase the ocean heat content. Feistel's consideration is based on a generalised Dalton equation (see Section 4) which uses a physically rigorous formulation of the thermodynamic driving force but still inheres several approximations of the "kinetic" prefactor in Daltons formula (see the empirical transfer coefficient as a function of wind speed in Eq. (6)). Classical approaches of the heat flux estimation relying on the Monin-Obukhov similarity theory in combination with a sophisticated treatment of the molecular layer at the ocean-atmosphere interface such as the renewal theory (e.g., Liu et al. 1979) will further complicate the situation: next to variations in the marine-surface layer RH also air and water temperature as well as wind variations may essentially contribute to the total heat flux uncertainty. A dedicated flux intercomparison analysis between the generalised Dalton approach, Eq. (6), and classical approaches is recommendable for subsequent studies.

Owing to its large heat capacity, the ocean serves as a superthermostat ensuring habitable temperatures on Earth. However, due to the superposition of multiscale waves in the ocean, the thermostatic performance of the ocean appears rather "erratic" which has implications, e.g., for the near-surface bucket temperature and the SST. As ocean currents are driven by atmospheric motions, changes in the atmospheric circulation (wind fields) may have a large impact on the water temperature and so on oceanic evaporation too. For me there is no doubt that a refined treatment of the ocean-atmosphere heat transfer is one of the keys to the elucidation of the reasons for the sudden ocean warming.

The author initiated and significantly contributed to the formulation of a roadmap toward a generalised SI-compatible RH definition which is based on rigorous thermodynamic notions. These basic notions are the four thermodynamic potentials presented in Section 2, allowing for a self-consistent formulation of the mutual thermodynamic equilibrium conditions for water in humid air, seawater and ice. A key role in the proposed generalised definition of RH plays the concept of fugacity. This notion allows a highly accurate full range-definition of RH in terms of relative fugacity with consideration of real gas effects. The classical formula for RH such as employed by WMO can be recovered from the relative fugacity for the limit of atmospheric pressure (ideal-gas limit). Even though the scientific background of relative fugacity and their approximations for practical use at atmospheric pressure were completely worked out and published in a series of peer-reviewed papers over many years, the formal adoption as a SI standard by the responsible international authorities remained, unfortunately, unrequited so far. The realisation of the final step of this roadmap remains desirable. I do not say a better way to define RH than by relative fugacity.

In Section 5.2 the author mentioned that evaporating sea spray droplets will "rather develop into a floating persistent Köhler (1936) equilibrium between droplet size, droplet salinity and ambient relative fugacity. This equilibrium can be described by the TEOS-10 model of sea air if the additional Kelvin pressure caused by the surface tension is allowed for." Just for authors information: more than a decade ago my former colleague Prof. A. K. Shchekin from Fock Institute of State University of St. Petersburg and his co-workers developed a full thermodynamic theory to describe the growth of soluble nanoparticles in a solvent vapor. The description is based on a generalisation of the Gibbs-Kelvin-Köhler theory of condensation and a generalisation of the Ostwald-Freundlich theory of solutions with consideration of the thermomechanic concept of disjoining pressure. Lateron this very sophisticated theory was extented to non-ideal solutions, combined with the theory of homogeneous salt crystallisation, and applied to the evolution of sodium chloride particles (as a proxy for sea spray) in ambient humid air (Hellmuth and Shchekin 2015, see references therein). This theory allows a full description of the size evolution of such hygroscopic particles from the dry initial state until the deliquescence threshold and back to the efflorescence threshold with disclosure of hysteresis effects. Independent of Rainer Feistels suggestions, the availability of TEOS-10 opens the challanging way to revise the approach of Hellmuth and Shchekin within the framework of a sensitivity analysis by replacing several properties of the theory with TEOS-10 based properties, among others by replacement of classical RH definition with the relative fugacity.

With reference to radiation models the author argued in Section 6 that on the global average the short-wave and long-wave cloud radiative effects cancel each other almost completely up to minor rest of -1 mW m^{-2} yr^{-1}, so that the observed continuously shrinking cloudiness (see Fig. 13) may be assumed to have practically no net effect on the ocean's radiation balance. Feistel added: "However, more detailed investigations in the future may reveal more rigorous results for the ocean than this simplified picture." In the context of authors argumentation it might be helpful to consider also a very recent study of Luo et al. (2024), who showed that in a warming climate low-level cloudiness exhibits diurnally asymmetric trends. According to them cloud fraction decreases more during the day than at night. Based on climate modelling, the diurnally asymmetric cloud cover variation was argued to be driven by trends in the lower tropospheric stability as a consequence of increasing greenhouse gas concentrations. This asymmetry turns out to be an amplifier of surface warming, by both decreasing the daytime cloud shortwave albedo effect and increasing the nighttime cloud longwave greenhouse effect. To complete the picture it might be useful to give reference to this study too.

In view of the high number of peer-reviewed TEOS-10 relevant papers which reflect the historical evolution of the development of this standard, the entry to this extraordinary achievement by different users is not easy. Although every physical detail is on the table, the time seems to be ripe for a user-friendly handbook to support the further application of TEOS-10 especially in the atmospheric community.

I found the study of Feistel very comprehensive and instructive and would like to see it accepted by the referees and the editor. My congrats to this further building stone in the TEOS-10 housing.

Technical

- Line 397: eq. (e4.6) is undefined

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