Ocean–Atmosphere Interaction

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Abstract
In this entry we define ocean–atmosphere interaction in terms of exchange of fluxes at the interface of ocean–atmosphere boundary and through compensatory dynamical circulations that maintain the observed climate of the planet. We describe the strong feedback between the atmosphere and ocean that is characterized in the fluxes, their global distribution of the fluxes, and diagnosis of the feedbacks.

INTRODUCTION

Ocean–atmosphere interaction commonly refers to the exchange of energy at the interface of the ocean and atmosphere. However, besides energy, there is also exchange of mass including that of fresh water (precipitation, runoff, melting of sea ice, evaporation) and of inert and sparingly soluble gases in seawater [e.g., oxygen (O_2), methane (CH_4), nitrous oxide (N_2O), carbon dioxide (CO_2)], which are quite significant even if they seem small on a unit area basis because of the extent of the ocean surface. We will, however, limit our discussion to the exchange of energy and freshwater. The energy exchange usually takes the form of exchange of heat (sensible heat), moisture (latent heat), and momentum (wind stress) at the overlapping boundary of the atmosphere and the ocean. The exchange of heat, moisture, and momentum are represented usually as fluxes, which are defined as the rate of exchange of energy per unit surface area of ocean–atmosphere interface. So the wind stress is the flux of horizontal momentum imparted by the atmospheric wind to the ocean. Similarly the latent heat flux refers to the rate at which energy associated with phase change occurs from the ocean to the atmosphere. Likewise the sensible heat flux refers to exchange of heat (other than that due to phase change of water) by conduction and/or convection. There is also heat flux from precipitation, which comes about as a result of the difference in temperature of the raindrops and the ocean surface. The heat flux from precipitation could become important in a relatively wet climate.

In the following sub-sections we discuss air–sea feedback, their global distribution, the common practices to diagnose this feedback, and the dynamical implications of ocean–atmosphere interactions, with concluding remarks in the final section.

AIR–SEA FEEDBACK

The surface energy budget of the ocean mixed layer of which sensible heat flux, latent heat flux, precipitation heat flux are a part of, dictates the temperature of the sea surface, which by virtue of its role in determining the stability of the lower atmosphere and the upper ocean dictates the fluxes across the interface. It may be noted that the surface ocean mixed layer of the ocean refers to the depth up to which surface turbulence plays an important role in mixing so that the density is approximately the same as the surface. The entire mixed layer is active in transferring heat to the ocean–atmosphere interface. This forms a feedback loop between sea surface temperature (SST), stability of the lower atmosphere and the upper ocean, and the air–sea fluxes. Therefore determination of air–sea fluxes is a form of diagnosis of the coupled ocean–atmosphere processes. Similarly, the fresh water flux is part of the ocean surface salinity budget that dictates the stability of the upper ocean, which feeds back to the air–sea fluxes. For example, the fresh water flux from river discharge into the coastal ocean results sometimes in forming a relatively thin fresh water "lens" or an ocean barrier layer[1] that stabilizes the vertical column and inhibits vertical mixing in the upper ocean. This ocean barrier layer is then relatively easily modulated by the atmospheric variations, thus modulating the SST and therefore the air–sea fluxes. The influence of cloud radiation interaction on SST is another form of air–sea feedback. Several studies,[2–4] for example, note the existence of positive cloud feedback on SST in the summer time over North Pacific (~35°N). This feedback refers to the reduction of SST under enhanced maritime stratiform clouds in the boreal summer season that reduces the downwelling shortwave flux and cools the mixed layer. In turn, the cooler SST favors further enhancement of the stratiform clouds affecting the stability of the atmospheric

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boundary layer. Wind Induced Surface Heat Exchange (WISHE) phenomenon is another form of air–sea feedback, which refers to the positive feedback between the surface (sensible and latent) heat fluxes with wind speed that results in increased fluxes leading to cooling of the SST as the wind speed increases. These negative correlations are apparent at large spatial scales across the subtropical oceans[5] as well as in mesoscale features (e.g., hurricanes).[6] The asymmetry of the inter-tropical convergence zone residing largely in the northern hemisphere in the eastern Pacific and in the eastern Atlantic Ocean was explained in terms of WISHE.[7]

DISTRIBUTION OF AIR–SEA FLUXES

Direct measurements of air–sea flux are few, limited both in time and in space. These measurements of air–sea fluxes are important, however, for developing, calibrating, and verifying the estimated air–sea flux from parameterization schemes.[8,9] The parameterization schemes for air–sea fluxes use state variables of the atmosphere and the ocean (e.g., wind speed, temperatures, humidity) to estimate the fluxes. A commonly used parameterization scheme for air–sea fluxes is the “bulk-aerodynamic” formulae. This is based on the premise that wind stress is proportional to the mean wind shear computed between surface and 10 m above surface, and sensible heat flux and latent heat flux are proportional to the vertical temperature and moisture gradients computed between surface and 2 m above surface. As a result, air–sea fluxes have been computed globally and regionally from a variety of analyzed and regionally observed or analyzed atmospheric and oceanic states leading to a number of air–sea flux intercomparison studies.[10–12] These intercomparisons provide insight into the uncertainty of estimating air–sea fluxes as well as revealing salient differences in the state variables used in the parameterization scheme. For example, Smith et al.[10] found that in many regions of the planet the differences in surface air temperature and humidity amongst nine different products of air–sea fluxes had a more significant impact than the differences in the surface air wind speed (at 10 m) on the differences in the air–sea fluxes. Climatologically, large values of sensible heat flux are observed in the winter along the western boundary currents of the middle-latitude oceans, when cold continental air passes over the warm ocean currents (e.g., Gulf stream). In the tropics and in the sub-tropical eastern oceans, the sensible heat flux is usually small. In the former region, climatologically, the wind speeds and the vertical temperature gradients between the surface and 2 m above the surface are weak. In the sub-tropical eastern oceans, with prevalence of upwelling, the SSTs are relatively cold leading to generally smaller sensible heat flux. The latent heat flux is observed climatologically to be large everywhere in the global oceans relative to the sensible heat flux, with exceptions over polar oceans in the winter season. The ratio of sensible to latent heat flux, called Bowen ratio, has a latitudinal gradient with higher (smaller) ratio displayed in the polar (tropical) latitudes. This gradient of the Bowen ratio largely stems from the decreasing SST with latitude that affects the moisture-holding capacity of the overlying atmosphere and thereby affecting the latent heat flux.

The higher Bowen ratio may lead one to believe that air–sea coupling is weak in regions of cold SST. However, several studies[13,14] reveal that this is not the case. Using satellite-based winds (scatterometer) winds and SST that affords high space–time resolution, a robust relationship (positive correlation) between surface wind stress and SST is revealed along major ocean fronts that display strong SST gradients. Such a positive correlation between SST and surface wind speed is suggestive of a vertical momentum-mixing mechanism, which allows atmospheric wind to adjust to SST changes across major ocean fronts.[15,16] In other words, static stability of the lower atmosphere is reduced as the SST warms, which results in intensifying the turbulent mixing of the fast moving air aloft that causes the surface wind to accelerate. Such positive correlations have been observed in many regions of the global oceans at relatively small spatial scales.[14] On the other hand, negative correlations of wind speed with SST is suggestive of the so-called WISHE phenomenon discussed earlier.

DIAGNOSIS OF AIR–SEA FEEDBACK

Cayan[5] showed that vast regions of the middle-latitude ocean surface temperature variability is forced by the atmospheric variations. He showed this by comparing local, simultaneous correlations of the monthly mean values of latent heat and sensible heat fluxes with time tendency of SST, that capture this interaction at spatial scales, which span a major portion of the North Atlantic and Pacific Oceans. The simultaneous correlation of SST with heat flux is shown to operate at a more local scale. Similarly, Wu et al.[17] showed that the atmospheric variability in the eastern equatorial Pacific is forced largely by the underlying SST variations, where simultaneous correlations of latent heat flux with tendency of SST is positive. This is in contrast to the tropical western Pacific Ocean where the correlations of latent heat flux with time tendency of SST is negative, suggesting that atmospheric variability is forcing the SST variability.

DYNAMICAL INTERACTIONS

Ocean–atmosphere interaction also happens through dynamics as illustrated in the case of Asian monsoon.[18] Here it is shown that in order to maintain the net heat balance of the coupled ocean–land–atmosphere Asian monsoon system, the ocean transports heat to the winter hemisphere of the Indian Ocean as comparable heat is released in the atmosphere of the summer hemisphere from the monsoonal convection. Similarly, Czaja and Marshall[19] demonstrate that atmospheric heat transport from tropical to higher latitudes is comparably higher to that by the oceans to maintain the observed latitudinal gradients of temperature and hence the general circulation of the Earth's planet. In other words, in both these examples, the ocean and the atmosphere is acting in tandem to maintain the energy balance of the climate system of the planet, exhibiting a manifestation of the coupled ocean–atmosphere processes. Another prime example of ocean–atmosphere interaction is the natural variability of the El Niño and the Southern Oscillation (ENSO), one of the largest and the most well-known interannual variations of the Earth's climate system, manifesting most prominently as the SST variability in the eastern equatorial Pacific Ocean. ENSO is a result of ocean dynamics and air–sea interaction processes,[20,21] which has a quasi-periodic oscillation with a period in the range of 2–7 years that affects the global climate variations.

CONCLUSIONS

Ocean–atmosphere interaction comprises a critical part of the Earth's physical climate system. ENSO variations that affect the global climate variability was first explained in terms of air–sea feedback in the equatorial eastern Pacific Ocean in the late 1960s. The first forays of predicting seasonal climate in the 1970s came from the hypothesis that through air–sea interaction, the persistent tropical SST anomalies would impart climate memory to the overlying atmosphere. Ever since, steady progress has been made in modeling (or parameterizing) and observing air–sea fluxes. Our growing understanding of the importance of air–sea interaction on observed climate variability has also led us to wean away slowly from a reductionist approach of developing component (such as atmosphere, land, ocean) models in isolation to coupled climate numerical models. The air–sea interaction happens not only at the interface of the atmosphere–ocean boundary through fluxes (defined as the amount of exchange of energy or mass per unit area) but also through compensatory dynamical circulations to maintain the observed climate of the planet.

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