GRANT/71/IN/45

Final report for 'Modeling studies of the effects of winds and heat flux on the tropical oceans', NAGW-916, R. Seager, PI.

Over a decade ago, funding from this NASA grant supported the development of the Cane-Zebiak ENSO prediction model which remains in use to this day. It also supported our work developing schemes for modeling the air-sea heat flux in ocean models used for studying climate variability. We introduced a succession of simple boundary layer models that allow the fluxes to be computed internally in the model and avoid the need to specify the atmospheric thermodynamic state. These models have now reached a level of generality that allows modeling of the global, rather than just tropical, ocean, including sea ice cover. The most recent versions of these boundary layer models have been widely distributed around the world and are in use by many ocean modeling groups.

1. Development of ocean models designed for modeling and understanding air-sea interaction and climate variability

In recent years we have completed several studies aimed at understanding how surface fluxes of heat and momentum influence the climate and variability of the global ocean. We have used the Lamont ocean general circulation model (a state-of-the-art GCM) coupled to a simple model of the atmospheric mixed layer. In this experimental set-up the air temperature and air humidity are computed alongside the sea surface temperature and the other ocean properties. This allows the surface fluxes to be determined internally and bypasses the constraints on the model SST that would be imposed by using observed air temperatures and humidities in the flux calculation. Our arrangement is ideal for simulations of forced ocean climate variability. Satellite-derived estimates of clouds, solar radiation and winds provide the forcing for the model. Indeed, our progress was made possible by the significantly more accurate estimates of surface fluxes provided by the remote sensing data. It is fair to describe our modeling efforts as a means to translate satellite derived data into estimates of upper ocean states and of ocean-atmosphere exchanges.

2. Modeling of the tropical oceans

We began with simulations of the climatologies of all three tropical oceans. We found that introduction of the advective atmospheric mixed layer model led to significant improvements over previous models that used a one dimensional model to compute the air temperature and humidity and, hence, the surface fluxes. Advection and horizontal mixing of heat and moisture in the atmosphere play an important role in determining how the atmospheric and oceanic boundary layers equilibrate to each other. Advection of dry air off west Africa was found to play an important role in determining the SSTs of the subtropical North Atlantic. Air-sea coupling extends the influence of the African continent far westward of what would be expected on the basis of atmospheric flow over a fixed ocean. Continuing our studies of tropical oceans we examined how greenhouse forcing would be expected to influence the tropical Pacific Ocean.

3. The tropical oceans and long long term climate change

Building on our work aimed at understanding the dynamics and thermodynamics of the tropical oceans, we demonstrated the conditions under which coupled equatorial dynamics, in concert with the SST and the surface fluxes, could lead to a delay, and possible reduction, of global warming. This involves a predicted increase in the rate of meridional overturning of the wind driven circulation above the thermocline that pumps heat into the thermocline region where it can remain for several decades before resurfacing. Some evidence was found that this theory agrees with the observed record of tropical Pacific SST changes over the twentieth century.

This work led us to a more theoretical investigation of how changes of tropical ocean heat transports could cause or influence climate change. We found that changing the meridional heat transport of the tropical oceans could cause significant changes in tropical mean temperatures but only via feedbacks involving the convecting atmospheric boundary layer, low cloud cover and the atmospheric water vapor greenhouse trapping. We hope to test these ideas in a full GCM and in satellite retrievals of clouds and water vapor as the data becomes available.

Building on our examination of how coupled equatorial dynamics are involved in the climate response to greenhouse warming, we have examined how the tropical Pacific and the El Niño-Southern Oscillation (ENSO) responds to changes in the Earth's orbit over the last glacial-interglacial cycle. We have shown that orbital changes, by altering the seasonal cycle of solar radiation, lead to a powerful response in the ENSO behavior. We are examining how these changes would impact the global climate. This is pioneering work in climate research in that tropical air-sea interaction has not previously been thought to play an active role in Quaternary climate change.

4. Understanding decadal variability of the Atlantic and North Pacific Oceans

Our most recent work on surface fluxes and air-sea coupling has involved a long simulation of Atlantic Ocean climate variability. We have found that changes in the atmospheric circulation are almost entirely responsible for the observed climate change via their impact on the surface heat fluxes. This is true for interannual variability as well as for decadal variability and is true in the tropical Atlantic as well as in the North Atlantic. Changes in ocean heat transport associated with anomalous Ekman drifts enhance the SST variability in the North Atlantic while advection of the anomalous SSTs by the mean circulation damps the SST changes in the tropics. The role of the ocean in North Atlantic climate variability appears to be passive. In the tropical Atlantic, while the ocean's role is dominated by advection by the mean currents, this may nonetheless be essential in maintaining decadal variability. This remains under investigation.

Climate variability of the North Pacific Ocean is similar to that of the North Atlantic. The SST variability can be understood in terms of atmospheric forcing by surface fluxes and anomalous Ekman drifts. This is true on interannual and decadal timescales and also for that portion of the variability that is independent of ENSO. As in the North Atlantic the role of the ocean appears to be passive.

5. Modeling of coupling between atmospheric storms, fluxes, SST and thermocline structure.

Currently we are examining the impact that atmospheric synoptic eddies and deep and shallow convection have on the surface fluxes and oceanic structure over the wintertime mid-latitude oceans. A storm parameterization has been incorporated into our AML model. Storms greatly enhance the wintertime surface fluxes and cool the SSTs. As a result winter mixed layers are deeper and the properties of waters transfered into the thermocline are altered. Indeed, storms appear responsible for creation of the mode waters.

6. Graduate students trained

This NASA award supported a graduate student, Amy Clement, who was awarded her Ph.D in 1999. It was awarded with a Distinction which is only the second time in the history of our department that such an award has been made.

7. Conclusions

Development of satellite radiation data sets has enable us to develop ocean models coupled to simple atmospheric boundary layer models that are highly useful in analyzing how SSTs have varied over the last several decades. As a result of the work we have performed we have developed a working hypothesis oh how global climate variability works. We believe that variability divides into tropical modes which are definitely coupled (the Pacific) and quite possibly coupled (the Atlantic) and mid-latitudes modes that are atmospheric forced and in which the ocean is passive and merely acts to redden the spectrum of variability. The mid-latitude modes combine purely internal variability and the atmospheric response to tropical forcing. This suggests that it will be possible to build an efficient global ocean model for studying climate variability, other than that associated with the thermohaline circulation, that involves complete dynamics in the tropical Pacific but only Ekman flows (mean plus anomalous) elsewhere. Such a model is under construction and, coupled to an atmospheric GCM, will be a useful tool in climate modeling.

8. Recent publications under NAGW-916 (1997 on)

Cane, M. A., A. C. Clement, A. Kaplan, Y. Kushnir, D. Pozdnyakov, R. Seager, S. E. Zebiak and R. Murtugudde, 1997: Twentieth century sea surface temperature trends. *Science*, **275**, 957-960.

Clement, A. C., M. A. Cane and R. Seager, 1998: Patterns and mechanisms of Twentieth Century climate change. *World Resource Review*, **10**, 161-185.

Clement, A. C., R. Seager and M. A. Cane, 1999a: Orbital controls on the El Niño/Southern Oscillation and the tropical climate. *Paleoceanogr.*, **14**, 441-456.

Clement, A. C., R. Seager and M. A. Cane, 1999b: Suppression of El Niño during the mid-Holocene by changes in the Earth's orbit. *Paleoceanography*, in press.

Clement, A. C. and M. A. Cane, 1999: A role for the tropical Pacific coupled ocean-atmosphere system on Milankovitch and millennial timescales: Part I: A modeling study of tropical Pacific variability. In Clark et al., Ed, *Mechanisms of global climate change at millennial timescales, Geophysical Monograph 112*, AGU, Washington DC.

Clement, A. C. and R. Seager, 1999: Climate and the tropical oceans. *J. Climate*, bf 12, 3383-3401.

Israeli, M., N. Naik and M. A. Cane, 1999: An unconditionally stable scheme for the shallow water equations. *Monthly Weather Review*, in press.

Seager, R., A.C. Clement and M. A. Cane, 1999: Glacial cooling in the tropics: exploring the roles of tropospheric water vapor, wind speed and boundary layer processes. *J. Atmos. Sci.*, **57**, 2144-2157.

Seager, R., Y. Kushnir, M. Visbeck, N. Naik, J. Miller, G. Krahmann and H. Cullen, 1999: Causes of Atlantic Ocean climate variability between 1958 and 1998. *J. Climate*, in press.

Seager, R., Y. Kushnir, N. Naik, J. Miller, P. Chang and W. Hazeleger, 1999: Looking for the role of the ocean in tropical Atlantic decadal climate variability. *J. Climate*, in press.
Seager, R., Y. Kushnir, N. Naik and J. Miller, 2000: Mechanisms of Pacific Ocean Climate variability between 1958 and 1998. *J. Climate*, in preparation.