AN INVESTIGATION OF A SUBSEASONAL FORECAST MODEL'S ABILITY TO REPRESENT LAND-ATMOSPHERE INTERACTIONS

by

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A Thesis submitted in partial fulfillment of the requirements for the degree of Master of Science at George Mason University

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DEDICATION

This is dedicated to my loving parents, for their unconditional love and support, and the sacrifices they made to make this possible.

ACKNOWLEDGEMENTS

I would like to thank the many friends, relatives, and supporters who have made this happen. Dr. Paul Dirmeyer, who was consistently supervising and encouraging me throughout the research process and providing me with the opportunity to learn under his tutelage. Dr. Ruixin Yang and Dr. Kathleen Pegion, members of my committee who were of invaluable help. Finally, thanks go out to Sally Evans for reviewing the format of this thesis.

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ABSTRACT

AN INVESTIGATION OF A SUBSEASONAL FORECAST MODEL'S ABILITY TO REPRESENT LAND-ATMOSPHERE INTERACTIONS

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A reanalysis of atmospheric and land-surface states is investigated to understand the water cycle, energy cycle and the role of the planetary boundary layer (PBL) in land-atmosphere interactions, and is used as validation for model forecast data. Subseasonal to seasonal (S2S) forecasts from an operational forecast model are examined to determine if they can replicate the relationships observed when using the reanalysis data. The ability of the S2S models to properly show relationships that indicate land-atmosphere interactions are crucial for forecasting extreme events, and understanding the conditions that allow for the intensification and persistence of these events. Daily noontime values of temperature, humidity, and surface fluxes were taken from the reanalysis dataset, as well as morning values of soil moisture over the contiguous United States. Potential evaporation and boundary layer properties are calculated and correlation analyses are carried out to determine the significance of these relationships to one another and to state variables. A similar investigation is carried out using daily averaged data from the S2S

forecast model. The reanalysis reinforces previous knowledge on the role of soil moisture and the boundary layer in land-atmosphere interaction over the continental US. Correlations (or anticorrelations) among terms involved in land-atmosphere interactions are strong in the summer months (June, July, and August) with gradients from either north to south, or west to east. The western US typically show that soil moisture and evaporation plays a role in the land-atmosphere interactions. The forecast model was inconclusive, with values of surface fluxes over the western and north-central US showing the possibility of issues in the way this model behaves. Overall, further studies need to be carried out on the forecast model to determine better ways to determine these relationships, or improve on the data products from the model.

CHAPTER ONE

Introduction

Extreme events like heatwaves and drought are not only important because of their adverse effects on life within the affected regions but also because of the overall impact on the larger scale systems and the corresponding effects on other regions around the globe. Atmospheric interactions with the land surface have a significant role in the formation or persistence of these extremes with soil moisture and the boundary layer (PBL) being the instruments that drive these interactions (Dirmeyer, 2011; Betts et al., 1996).

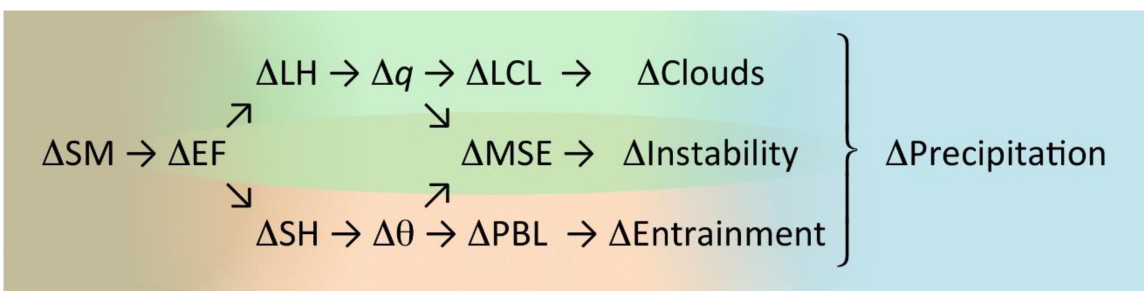


Figure 1: The chain of land-atmosphere interactions from soil moisture to the top of the boundary layer.

Figure 1 shows how soil moisture affects the boundary layer and its properties. A change in soil moisture (SM) leads to changes evaporative fraction (EF) through both the sensible heat flux (SH) and the latent heat flux (LH). These changes in surface fluxes affect the amount of moisture (specific humidity q) and heat (potential temperature θ) in the lower atmosphere. The amount of moisture and heat in the atmosphere determines the height of the lifting condensation level (LCL) at which clouds can form, the boundary layer depth (PBL), and the amount of moist static energy (MSE) in the boundary layer. This process determines whether there is enough instability for the formation of clouds, or the moist warm air is dried out by entrainment at the top of the boundary layer (Santanello et al., 2011). A thorough examination of soil moisture, surface fluxes, convective processes, and radiative activities will be essential in understanding the role of the PBL in these extreme events. This knowledge will improve our ability to determine precursors to these events and effectively generate more skillful forecasts geared towards useful applications by decision makers.

This research investigates the water cycle, energy cycle and the role of the PBL as a driver to the intensification or sustenance of drought and heatwaves which are extreme conditions related to these cycles. The PBL is influenced via surface fluxes by the soil moisture, which is largely a function of the prevailing precipitation and the heating of the Earth's surface which is as a result of solar radiation (Betts et al., 1996). The energy required to evaporate the water from the Earth surface and the energy required to warm the PBL from the bottom creates an interactive system between the land surface and the PBL that ultimately affects the depth of the boundary layer, the amount of precipitation, the amount of soil moisture, and the air temperature within certain regions on the land surface (Dirmeyer et al., 2013). As much as it is acknowledged that synoptic systems have their effects on these processes as a whole, the major focus of this research is on the depth of the PBL, the latent and sensible heat fluxes as driven by solar radiation and the interaction that occurs between the land surface and the PBL above it. It is expected that this relationship between the land surface and the PBL will be a significant factor that could possibly drive connections between heatwaves and droughts, and a proper investigation of these interactions will provide the knowledge required for better parameterizations in models.

In the remainder of the Thesis, Chapter 2 will describe the data used for this study, and provide details about the study area. Chapter 3 will discuss the methods, calculations and analyses used in the research, while Chapter 4 will show the results obtained during the investigation. These results will be grouped into 3 sections, the water cycle, the energy cycle, and the boundary layer. Chapter 5 will discuss the meaning of the results and where they lie in relation to the ongoing discussions on this topic in the community. Chapter 6 will summarize the results and the highlights during the process of the research.

CHAPTER TWO

Data

Modern-Era Retrospective Analysis for Research and Applications, version 2 (MERRA-2) Reanalysis

Reanalyses are an integration of remotely sensed satellite-based data and standard in-situ weather observations that are incorporated into a numerical model that provides global atmospheric and Earth related datasets (Bosilovich et al., 2015). The MERRA-2 reanalysis made available by the National Aeronautics and Space Administration (NASA), is produced with the Goddard Earth Observing System version 5.12.4 (GEOS-5.12.4) atmospheric data assimilation system. The spatial resolution of this model is $0.5^0 \times 0.625^0$ using a finite-volume dynamical core, and an hourly temporal resolution from 1980 through to the present. Noticeable differences between MERRA-2 and its previous version include its use of observed precipitation as the driver for the surface water budget, and significantly improved surface and root-zone soil moisture, products that are essential in this investigation. The MERRA-2 reanalysis is taken as "observed" data and used to validate the products obtained from the forecast model. Its relatively high spatial and temporal resolution allow for a good representation of the relationships analyzed in this study. Noontime values of reanalysis and morning values of soil moisture are acquired and analyzed in this study.

National Centers for Environmental Prediction (NCEP) Subseasonal to Seasonal (S2S) Forecast Model

The Subseasonal to Seasonal (S2S) prediction project was initiated to meet the demands for forecasts that are reliable and tailored for societal applications, particularly weather-related hazards. The dearth of skillful forecasts between medium and long-range weather is another issue this project is hoping to solve by providing coupled atmospheric and ocean models. The medium-range forecasts of the S2S project are modeled on The Observing System Research and Predictability Experiment (THORPEX) Interactive Grand Global Ensemble (TIGGE) database, and the seasonal forecasts on the Climate-System Historical Forecast Project (CHFP). Some of major topics researched regarding predictability by the project include the Madden-Julian oscillation (MJO), and the El Niño-Southern Oscillation (ENSO) (Vitart et al., 2017).

The S2S database contains medium-range weather to seasonal forecasts from 11 operational centers aimed at filling the gaps of forecasts on the subseasonal timescale, and improving the knowledge of decision makers (Vitart et al., 2017). The NCEP Climate Forecast System version 2 (CFSv2) proves to be an upgrade from the previous version as it boasts of an upgraded four-level soil model, three-layer sea ice model, and historically prescribed CO_2 concentrations (Saha et al. 2014). NCEP's atmospheric forecast model has a ~100km grid resolution based on a triangular truncation of T126 and a run frequency of 4 times/day, each forecast is up to 45 days. With a 6-hourly temporal resolution and data ranging from 1999 to 2010, daily values of forecasts are acquired from the S2S database at ECMWF. The dataset is analyzed at 2-day, 10-day, and 28-day leads, and compared to the results obtained from the MERRA-2 reanalyses.

This study was carried out on a subset of the global dataset over the contiguous United States (spanning 24^0 N–50^0 N, 125^0 W–70^0 W) for 12 years ranging from 1999 to 2010. Daily averaged data was obtained from four ensemble members, time averaging was carried out separately for each ensemble member and statistics were calculated using methods described in the following chapter. Finally, the 4 ensemble members were averaged together and summer months (June, July, and August) were used for the analysis.

CHAPTER THREE

Methods

In this study, the NCEP model forecasts at three different lead times are used: 2-day lead, 10-day lead, and 28-day lead, which allow for understanding the evolution of model behavior and bias after its initialization. Investigating the model at these lead times showcases the model's predictability and forecast skill, providing a range of days of reliable forecasts and an avenue to monitor the model's climate. Some terms, such as EF and net radiation, were not available in the model output and had to be calculated from the available variables. The statistics of means, temporal variance, covariance, standard deviation, and correlation shown in Table 1 allow for the validation of the NCEP model for individual variables and coupled behavior for pairs of variables presented in the correlation analysis, using the coupling indices developed by Dirmeyer (2011b). They were formulated such that calculations using the very large reanalysis and forecast data sets described in Chapter 2 would be done in one programming loop instead of two, and provide overall computational efficiency.

Potential Evaporation

Evapotranspiration is essential to our understanding of how the land and the atmosphere interact. The transfer of energy by surface fluxes from the ground to the atmosphere directly above it and ultimately across the boundary layer is largely influenced by the partitioning of evaporation, hence its importance in this study. The potential evaporation (E_p) as derived by the Priestley-Taylor formulation for wet surface (Eq.1 below; Priestley & Taylor, 1972) relies solely on net radiation and temperature, and the ability for a wet surface to evaporate at its potential rate. An accurate estimation of E_p is required for understanding the dynamics of heat and energy transfer (Wang et al., 2006). In Equation 1, the net radiation *Rnet* and temperature *T* are obtained from the reanalysis and forecast model outputs, while saturation vapor pressure e_s is derived from temperature using the Clausius-Clapeyron equation.

Equation 1: Priestley-Taylor formulation for wet surfaces

$$E_p = \alpha \frac{mRnet}{\lambda v(m+\gamma)} \quad \textit{where} \quad m = \frac{de_s}{dT}$$

where:

α = Priestley-Taylor coefficient
Rnet = Net radiation
m = Slope of saturation vapor pressure with temperature at surface temperature T
λv = Latent heat of vaporization ≡ 2.5×10^6 J/kg
γ = psychrometric constant = 65 Pa/K

Priestley-Taylor coefficient

The Priestley-Taylor equation was derived to estimate potential evaporation in conditions where advection is limited. As a rule of thumb, a dimensionless Priestley-Taylor coefficient (α) was a parameter used to indicate a surplus of water available for evaporation (Stannard, 1993), with α approximated to be 1.26 in areas with minimal advection and 1.76 in very wet regions. However, a more accurate formulation for α (Eq. 2 below; Betts, 2004) is used in this study, as it provides a more realistic estimate.

The evaporative fraction λE/(H+λE) and a term based on the slope of specific humidity (1+ε/ε) are important components of the Priestley Taylor (P-T) coefficient and determined the amount of energy and moisture available for evaporation. This coefficient is also largely responsible for determining the height of the LCL, and the corresponding depth of the PBL, both of which are significant for the formation of clouds and boundary layer dynamics. All the variables in Eq. 2 are from the reanalysis and model output, except the thermodynamic coefficient that is derived from specific humidity and temperature.

Equation 2: Priestley-Taylor coefficient

$$\alpha = \frac{\lambda E}{H+\lambda E}\,\frac{1+\varepsilon}{\varepsilon}, \quad \varepsilon = \frac{\lambda_v}{C_p}\,\frac{dq}{dT}\Big|T_{LCL}$$

where:

λE = Latent heat flux
H = Sensible heat flux
ε = Thermodynamic coefficient
q = Specific humidity
T = Temperature at the height of the LCL
C_p = Specific heat of air at constant pressure =1010 J/Kg/K

Correlation Analysis

Correlation analysis is carried out to determine how variables within the PBL are affected by variables within the water and energy cycle, and the role of soil moisture in the water and energy cycles and PBL through the investigation of the surface fluxes. One key property of the PBL that will be of interest is the P-T coefficient which represents the amount of moisture available for evaporation or the likelihood of cloud formation and occurrence of convective activities (Betts et al., 1996). The role of the P-T coefficient and the height of the LCL are investigated as the PBL interacts with the energy and water cycle, and the evaporative fraction induced by net radiation (Santanello et al., 2009).

Table 1: Quantities derived to calculate correlations

Description	Expression
Means	$\bar{X}_{(m=1,12)} \frac{1}{N \cdot K} \sum_{k=1}^{DOM} \sum_{N=1}^{Years} X$ $\overline{X^2}_{(m=1,12)} \frac{1}{N \cdot K} \sum_{k=1}^{DOM} \sum_{N=1}^{Years} X^2$, where m is month (1…,12)
Variance	$V_x = \overline{X^2} - \bar{X} \cdot \bar{X}$
Covariance	$Cov_{xy} = \overline{XY} - \bar{X} \cdot \bar{Y}$
Standard Deviation	$\sigma_x = \sqrt{V_x}$
Correlation	$r = \frac{Cov_{xy}}{\sigma_x \cdot \sigma_y}$

Table 2 shows how the correlation analysis is being utilized to investigate the water (soil moisture) and energy (net radiation and temperature) cycles, and the boundary layer influence (specific humidity and P-T coefficient). Only a select number of these correlations will be discussed extensively in the results section; primarily relationships that are significant and/or highlight the role of the boundary layer as a driver for the land-atmosphere interaction or the lack thereof. Correlations between other terms from the reanalysis are shown in the Appendix.

Potential Sensible heat flux

The potential sensible heat flux was developed by Miralles et al, (2012) as part of an energy term in a coupling metric to examine the potential effect of soil moisture on temperature in heat waves. It can also be regarded as the sensible heat flux for anomalously high temperatures. It is defined as:

Equation 3: Potential sensible heat flux

$$H_p = R_n - \lambda E_p$$

where:

H_p = Potential sensible heat flux
λE_p = Potential latent heat flux
R_n = Net radiation

Table 2: Table showing the pairings for correlation analyses

Variable	Correlations

Soil moisture	Soil moisture and Priestley Taylor coefficient Soil moisture and Latent heat flux
Specific Humidity	Specific humidity and Latent heat flux Specific humidity and Potential latent heat flux Specific humidity and Sensible heat flux
Priestley Taylor Coefficient	Priestley Taylor coefficient and Evaporative fraction Priestley Taylor coefficient and Latent heat flux
Net Radiation	Net radiation and Latent heat flux + Sensible heat flux
Temperature	Temperature and Latent heat flux Temperature and Potential Latent heat flux Temperature and Sensible heat flux Temperature and Potential Sensible heat flux

CHAPTER FOUR

Results

An investigation of the relationships described above within the contiguous US should highlight regions of strong land-atmosphere coupling, i.e. hotspots (Koster et al., 2006), especially during the summer months. Similarly, certain regions should show some form of connection between heatwaves and drought with the land surface and PBL playing significant roles in those interactions. Regions where the boundary layer depth and the height of the lifting condensation level are highly correlated should also be established, allowing for more skillful predictions from models.

Water cycle

Soil moisture, which is largely driven by and responsible for precipitation, is a huge indicator for the direction of flow of the water cycle. Soil moisture's interaction with the surface fluxes also serves as a link to the energy cycle at the earth's surface (Dirmeyer et al., 2013). A positive correlation between soil moisture and the surface fluxes, particularly latent heat flux, or the properties of the boundary layer is indicative of a moisture limited region (Dirmeyer et al., 2009). This implies that there is sufficient available energy to evaporate water from the earth surface, but there is limited amount of moisture in the soil. In the case of droughts, moisture limited regions create a positive feedback where there are less convective activities as a result of the soil moisture deficit, which in turn reinforces the drier soils. Regions that are moisture limited have the potential to experience intensification and/or persistence of droughts. This is characteristic of the western US and arid to semi-arid regions. A negative correlation is indicative of the opposite. It suggests that there is surplus moisture in the region, such that little to no energy is required to evaporate the moisture thereby causing the region to be energy limited. Energy limited regions indicate that the soil plays little part in the climate of that region and most activities would likely be as a result of atmospheric conditions.

Figure 2 shows the correlation between soil moisture and surface latent heat flux. The MERRA-2 reanalysis data (left) and 2-day lead forecast (right)both show that the Western US is more moisture limited hence the positive correlations. This can be attributed to the arid regions in that area west of the Great Plains and the regions where correlations are strongest is slightly shifted to the east in the model outputs. As the lead time increases, the model loses its ability to effectively predict this relationship. The NCEP forecast model depicts a sharper west-east gradient with a significant transition zone along the Great Plains from north to south. The western part of the contiguous US is largely moisture limited and shows strong positive correlations similar to results from the reanalysis, while the eastern part of the US is largely energy limited.

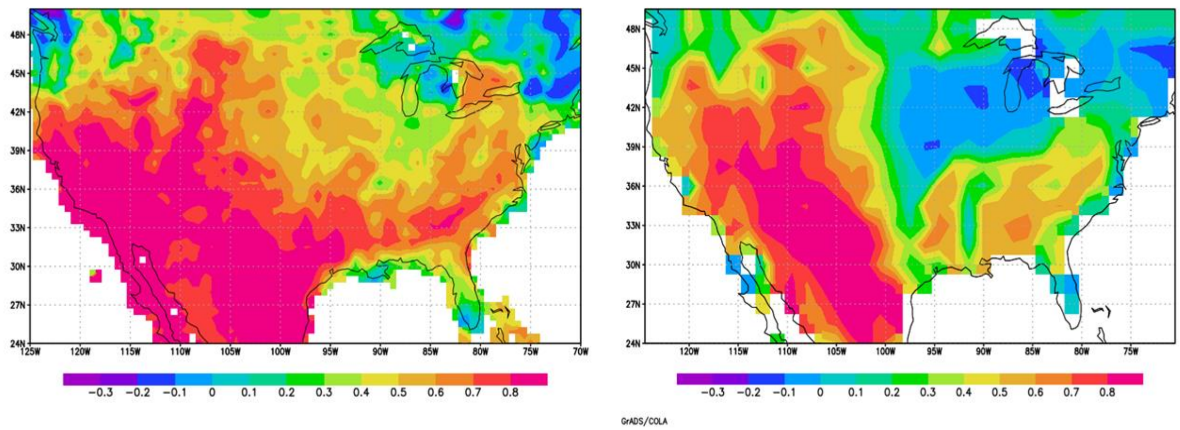


Figure 2: Correlation of soil moisture and latent heat flux from MERRA-2 reanalysis (left), and NCEP 2-day lead forecast (right).

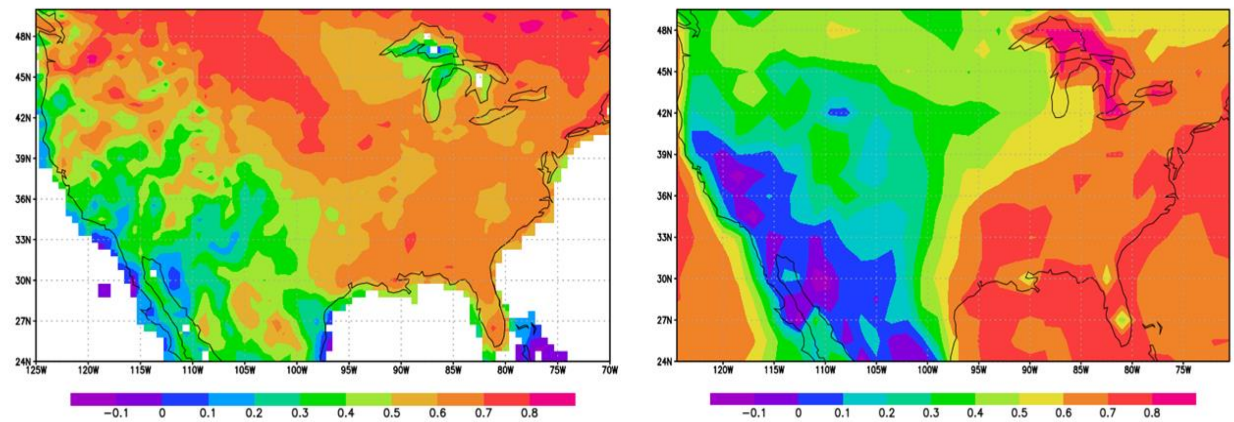


Figure 3: Negative of correlation of specific humidity and sensible heat flux displayed as in Fig. 2.

Negative values of the correlations (that is, correlation times -1), are used in Figure 3 to maintain the same color scales across all figures, with the reanalysis and models arranged as in Fig.2. The figure shows the correlation between specific humidity and sensible heat flux. Here, it appears that the water content in the atmosphere and the sensible heat from the land surface are more strongly linked in colder and wetter regions across the US in the summer months. The largely drier western part of the US seems to be weakly correlated as well as the coastlines. This is expected as the air is usually drier, or the land surface cooler in these respective regions.

Compared to Fig 2, the forecast model represents similar patterns and remains fairly consistent across all lead times. However, the magnitude of the correlation or lack thereof seems to be exaggerated by the models. Correlation is really poor in the northern US and really strong over the Great Lakes, which might be an indication of issues with initialization of the models. The Great Lakes temperatures are specified boundary conditions in the NCEP model with evaporation occurring at the potential rate, therefore they do not respond to changing atmospheric states nor close the surface water and energy budgets. This is most likely the reason for the exceptionally high correlations seen there. Regions that are strongly correlated in the model are shifted farther to the east. The forecast model has poor skill in predicting this land-atmosphere relationship of the water cycle, and at it stands, is significantly inconsistent with the reanalysis.

Energy Cycle

The energy cycle describes the transfer of heat from the land surface to the atmosphere and vice versa. It basically describes the direction of heat flow, which ultimately affects the water cycle via the rate of evaporation, and drives the boundary layer processes. Net radiation and temperature play major roles in the interactions with the surface fluxes, and the inflow/outflow of heat into/out of the boundary layer is significant in determining the connection between the land and the atmosphere.

Figure 4 shows the correlation of temperature and sensible heat. Positive correlations indicate that air temperature is strongly connected to land surface heating and could be attributed to the occurrence or persistence of extreme heat events. The MERRA-2 reanalysis shows a significant correlation in the southern and southeastern US and connections grow weaker as they spread northward. The West Coast and the region surrounding the Great Lakes show no correlation, hence little to no connections between the land surface heating and temperature. The 2-day lead forecast of the NCEP model mirrors this relationship but at lesser magnitudes. The region of correlation is also limited to the far south, and as the lead time increases the forecast model becomes more inaccurate in representing this relationship.

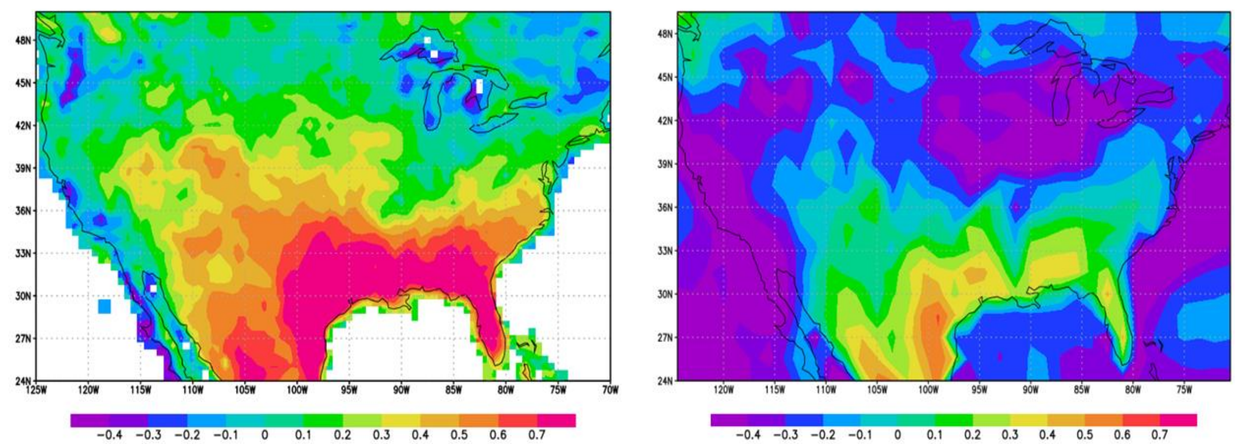


Figure 4: Correlation of Temperature and Sensible heat flux displayed as in Fig. 2.

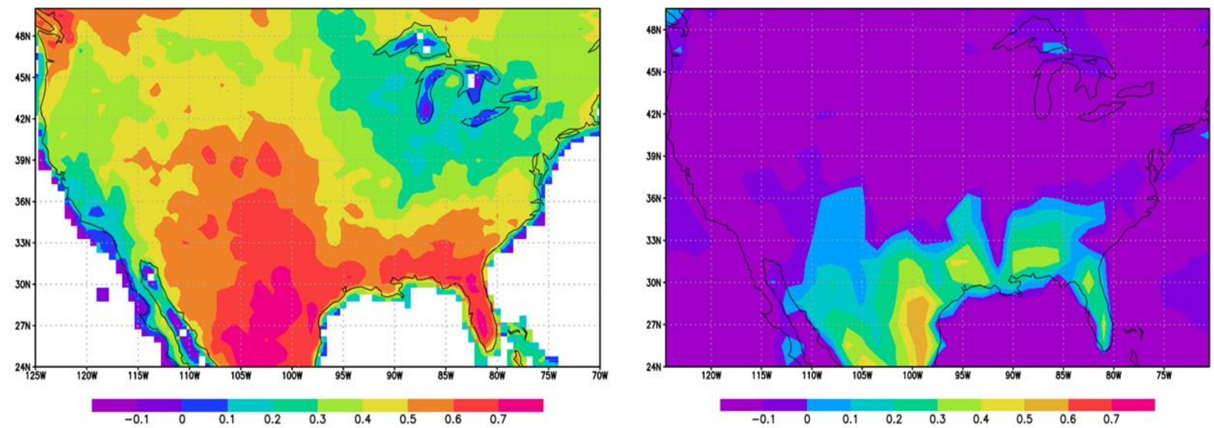


Figure 5: Correlation of Temperature and potential Sensible heat flux displayed as in Fig. 2.

The idea of surface sensible heat flux acting as a driver for air temperature under stable atmospheric conditions (Miralles et al., 2012), suggests that a region with strongly correlated air temperature and potential sensible heat flux will provide the skill for the prediction of heatwaves. This is also strongly linked to the soil moisture-temperature coupling (Seneviratne et al., 2010), as it is believed that soil moisture deficits create a positive feedback that further increases air temperature.

In Figure 5, the reanalysis (left) shows strong correlations in the South and Southeast indicating the potential for soil moisture to significantly affect the persistence and occurrence of heatwaves. The results show that over the North, Northeast and California, the land surface is not responsible for the occurrence of heatwaves and they might be attributed solely to atmospheric conditions. The forecast model's attempt to replicate this coupling of temperature and sensible heat fails dramatically, with the 2-day lead showing weak correlations in the Southeast. This may also contribute to the model's poor ability to predict the persistence of heatwaves (Ford et al., 2017).

Boundary Layer

The evolution of the boundary layer is largely determined by the entrainment at the top of the boundary layer and the amount of heat and moisture fed into the PBL from the surface. A close look at the P-T coefficient will allow for the observation of the amount of moisture that is fed into the PBL. While entrainment dries out the PBL from the top of the boundary layer, it leaves room for more intake of heat and moisture from the land surface, thereby lifting the LCL and creating a deeper boundary layer. Understanding how the boundary layer, through the P-T coefficient, interacts with the surface fluxes and components of evaporation would be paramount to understanding the role of the boundary layer as a link in land-atmosphere interactions.

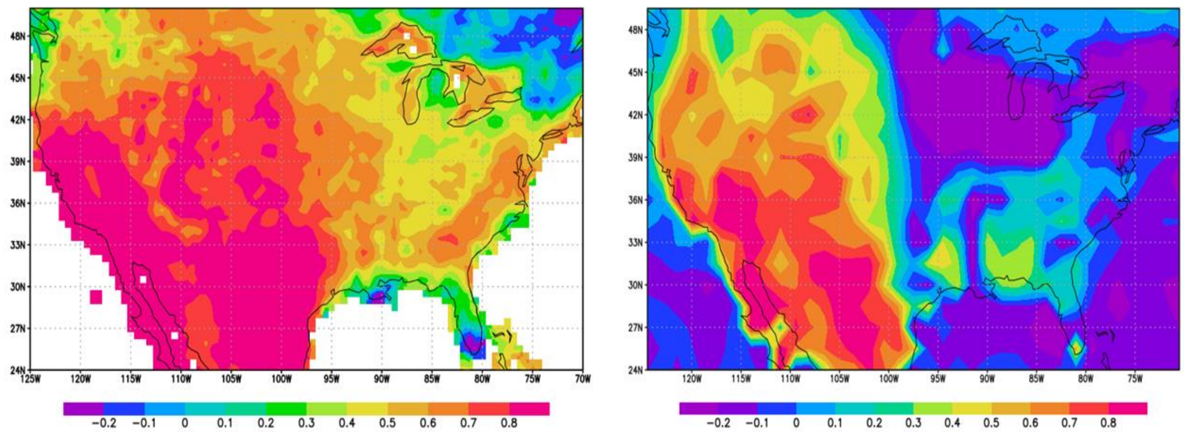


Figure 6: Correlation of P-T coefficient and latent heat flux displayed as in Fig. 2.

The correlations between P-T coefficient and latent heat flux are shown in Figure 6. The reanalysis indicates that there is a strong link between the boundary layer and the land surface along the West-Midwest-southern US, while the rest of the US is still relatively linked except Florida, southern Louisiana, and parts of Canada northeast of the Great Lakes. This strong correlation might explain the persistence of drought in the western regions as there is sufficient energy to readily evaporate whatever water is available at the surface, while entrainment is ongoing at the top of the growing PBL, hence the deepening and drying out the boundary layer. The positive feedback leads to less rainfall and soil moisture in the region.

This appears to be the case as well for the NCEP model. Although the correlations seem to be more restricted to the west and strong over less area, the overall pattern is somewhat similar. It is however, more strongly uncorrelated on the eastern part of the United States. The forecast model looks to be more consistent through the lead day changes in its prediction of this relationship, save for some of the area of significantly lower correlations in the southeast from Louisiana up north to Arkansas, and southwest of the Great plains.

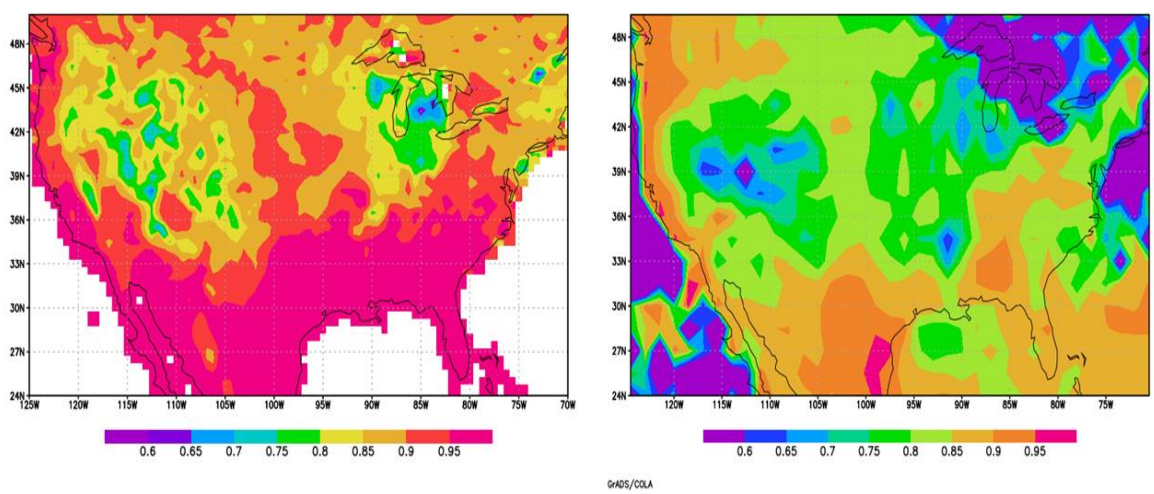


Figure 7: Correlation of P-T coefficient and Evaporative fraction displayed as in Fig. 2.

Figure 7 shows the correlation of P-T coefficient and evaporative fraction. The results show that P-T coefficient and evaporative fraction are strongly correlated over the entire US, which makes sense because any available water for evaporation would be evaporated provided the surface fluxes are present. The model however, seems to differ only in magnitude and seems to exaggerate areas of relatively weaker correlations. These areas spread as the lead time increases.

CHAPTER FIVE

Discussion

The correlations observed in the results correspond with previous findings that suggest a coupling of the land and atmosphere through surface fluxes and the boundary layer in summer months. It was also determined that soil moisture does not play a significant role in the persistence of heatwaves across the majority of the United States and it may be largely due to atmospheric conditions. Soil moisture however, cannot be written out as only surface soil moisture was investigated and soil moisture memory was not taken into account. Alternative coupling indices can also be explored. The results also suggest that the land-atmosphere interactions in the western and southern parts of the United States are more land driven (moisture limited) while the eastern part of the US is more energy limited.

The inconsistency of the NCEP model and its inability to maintain skill past the 2-day lead is characteristic of model drifts. The actual reason for this inconsistency and drifts in the longer-day forecasts is yet to be determined and requires further investigation, thus results from the longer-lead forecasts are not presented here. Parameterizations should also be made to strongly take into consideration the underlying physical processes that are represented by these variables.

The NCEP model was also found to have certain areas that always seemed to have relatively lower correlations, particularly in the Midwest, over Louisiana and southern Arkansas, and west of the Great Plains over Utah and Nevada. In the Midwest, northern Great Plains and Mississippi Valley this is probably a result of the model's representation of deep roots and free evaporation for the crop vegetation type (Dirmeyer & Halder, 2017), leading to shallow boundary layers and (over/under) compensating for certain parameters in those regions. The cause for the differences over the western US are not clear.

The NCEP model does have the potential to accurately represent the land-atmosphere relationships, as some of the correlations from the forecast showed especially at the 2-day lead. With better initializations and improvements made towards reducing model drift, such as implementing drift correction methods, the model should be able to provide better forecast of land-atmosphere coupling which would be very significant for the prediction of heatwaves, droughts and other extreme events that could adversely affect nature, human health and productivity, and the economy.

CHAPTER SIX

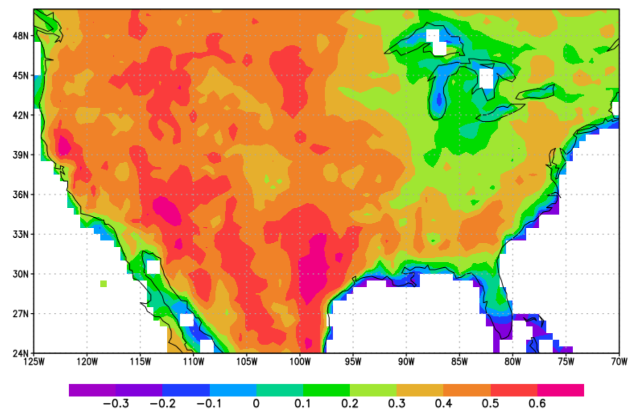
Conclusion

The NCEP forecast model's ability to predict land-atmosphere interaction is at best limited at this point and the model itself appears to be a larger contributor to the errors than the initial conditions. A global investigation of its abilities would be helpful in understanding if there are any issues that are particular to the contiguous United States alone. Other coupling indices and ways of determining the connections between the land and the atmosphere can also be developed to provide a well-rounded approach to the investigation of this S2S model. An example would be developing an estimation for the Priestley-Taylor coefficient that would provide better accuracy over arid regions. Forecasting in the S2S timescale is an area that still needs general improvement and a study of the available products, including additional forecast models, would be essential to gauging where we are now and the amount of progress that remains to be achieved.

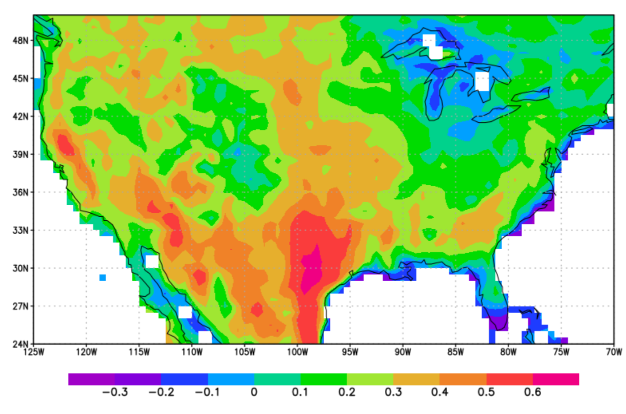
Some of the results arrived at in this study, such as the reason for low correlations over western US and strong evidence of model drift, are inconclusive and it would require further investigation to determine just how well the model performs. The role of the land surface in understanding our atmosphere and climate however, cannot be understated. More climate research centers need to pay close attention to the coupled land-atmosphere behavior of their models.

APPENDIX

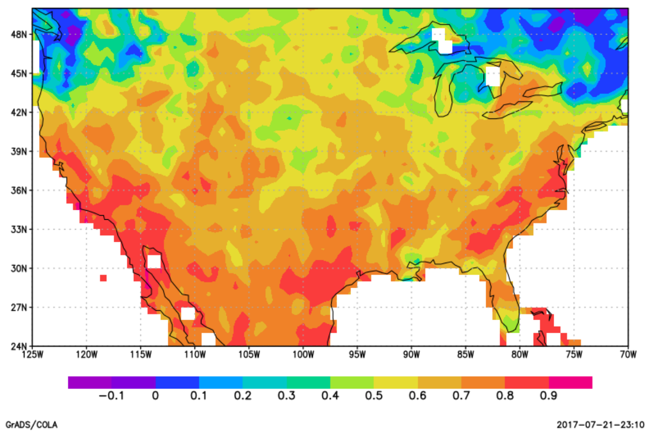
Additional correlation maps are presented here that were not discussed in the main text but supplement the analysis.



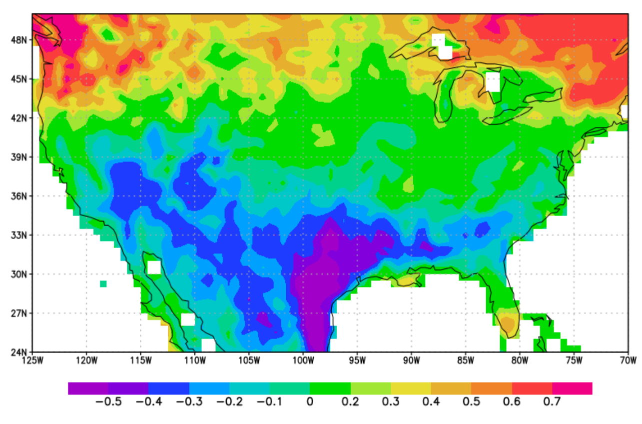
Appendix 1: MERRA-2 reanalysis showing correlation of specific humidity and potential latent heat flux



Appendix 2: MERRA-2 reanalysis showing correlation of specific humidity and latent heat flux



Appendix 3: MERRA-2 reanalysis showing correlation of soil moisture and P-T coefficient



Appendix 4: MERRA-2 reanalysis showing correlation of temperature and latent heat flux

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