P2.5 Data assimilation scheme of satellite derived heating rates for soil state initialization in a regional atmospheric mesoscale model: methodology.

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1. INTRODUCTION

Numerical Weather Prediction (NWP) models have been used since late '70s as a major tool for supporting human activities. Since the very beginning the NWP models have represented one of the main issue to improving forecast skills. Most of such effort is attempted by large national and international centers that manage large data sets and different sources: satellites, weather station, radio-sounding, radar which are ingested into models through complex data assimilation methods.

At global scale, soil initialization plays a major role on medium to long term simulations while at regional scales such impacts are important at shorter time scales affecting forecast skills especially on surface variables as described in several papers Avissar and Schmidt (1998), Chen and Avissar (1994), Golaz et al. (2001), Pielke et al. (2001), Koster and Suarez (2004), Xue et al.(2004). Further more such sensitivities are larger on those NWP models which include a detailed descriptions of soil – vegetation – atmosphere interactions schemes. As a consequence a reasonable description of the initial state is therefore crucial to improve forecasts reliability.

For case studies the general approach is to establish a reasonable choice of the initial soil state based on available datasets, retrieved from satellite, weather stations or specific soil state bulletins. Another strategy is to derive the initial soil state from Global Circulation Models, but such fields are generally not due to real observed precipitation fields and with a coarse spatial resolution.

Recently a special version of RAMS model has been implemented in order to compute soil state, at the starting time, according to a satellite rainfall estimates forcing, following the "Antecedent Precipitation Index" method (Pasqui 2004a).

Here an alternative satellite data assimilation method has been developed, for the Regional Atmospheric Modelling System (RAMS), which incorporates satellite – observed heating rates in order to retrieve soil moisture. It is based on the new generation of geostationary Meteosat Second Generation data, taking advantage of their enhanced spatial and temporal resolution.

The method acts on the soil moisture in RAMS ground levels adjusting it, upward and downward, until the RAMS simulated surface heating rate is in close agreement with the satellite – observed one in each grid cell. The method simply carries out a forward integration of the Soil – Vegetation – Atmospheric RAMS component (the Land Ecosystem Atmosphere Feedback version 2 model, LEAF2) for a special assimilation period in order to adjust the model soil moisture according with the observed data. Iterations needed add just a small amount of time to be computed to the total simulation time.

2. THE RAMS MODEL

The Regional Atmospheric Modeling System, RAMS, has been used operationally at La.M.M.A. (http://www.lamma.rete.toscana.it), the regional meteorological service of Tuscany (Italy) since 1999 in collaboration with the Institute of Biometeorology of National Research Council (http://www.ibimet.cnr.it) (Pasqui et al. 2000, Meneguzzo et al. 2004, Meneguzzo et al. 2001, Pasqui et al. 2002, Soderman et al. 2003, Pasqui et al. 2004a, Pasqui et al. 2004b, Pasqui et al. 2004c).

RAMS and its predecessors have been developed since the early '70s essentially as a research tool; nowadays the model is widely used both for research and operational forecast purposes in many meteorological centers around the world. Since early '90s a large number of improvements have been introduced from both the physical (new numerical schemes) and the computational point of view (the parallel computing design). A general description of the model can be found in Pielke et al. (1992), while a technical description can be found on the ATMET web site (http://www.atmet.com).

Today RAMS represents the state-of-the-art in the atmospheric numerical modeling and it is continuously improved on the basis of a multi-disciplinary work both at Colorado State University and at several other research laboratories worldwide. In synthesis, the physical package of the model describes a number of atmospheric effects: a two-way interactive nested grid structure, an atmospheric turbulent diffusion processes according with the Mellor-Yamada scheme, a cloud microphysics parameterization, modified Kain-Fritsch type cumulus parameterization, the Harrington radiative transfer parameterization short and long wave scheme and the Land Ecosystem Atmosphere Feedback scheme (LEAF2) for soil – vegetation –

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atmosphere energy, moisture exchanges, and surface heterogeneities connected to the vegetation cover and the land use.

The LEAF2 model (for a complete description of version 2 see Walko et al., 2000) represents the vertical exchange of water and heat in several soil layers, including the effects of freezing and melting, the temporary water and snow cover, the vegetation and the canopy air. The surface domain meshes are further sub-divided into patches, each identified by a separate vegetation cover and land use, soil type, initial soil moisture and temperature (Fig.2.1).

The balance equations for soil energy and moisture, surface water, vegetation and canopy air, and exchange with the free atmosphere, are solved separately for each patch. The LEAF2 model assimilates standard land use datasets to define the prevailing land cover (for instance the USGS dataset) in each grid mesh through the relative patches distribution. Then it parameterizes the vegetation effects by means of biophysical quantities.

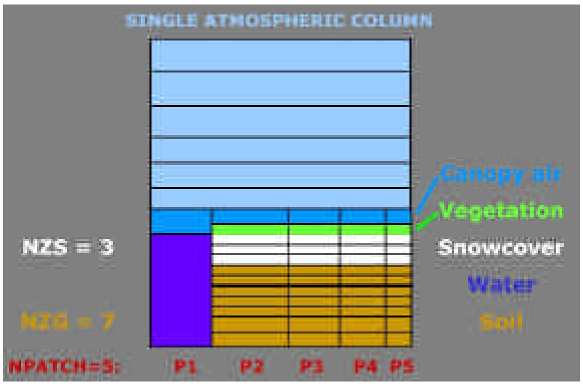

Fig. 2.1. LEAF vertical levels and patches scheme for a single RAMS column with eleven soil levels.

The precipitation produced by both convective parameterization and bulk microphysical scheme, within the column grid, falls down on the vegetation coverage, producing a moisture fluxes and energy due to the different hydrometeors.

Such fluxes are first partitioned between water at ground and vegetation according to the vegetation fractional cover. Moisture on the vegetation surface is evaluated and, when the combination of intercepted and dew formation exceeds the maximum amount that vegetation can hold, that amount of moisture is brought to thermal equilibrium by heat transfer with vegetation and then collected in the surface water category. The sub grid heterogeneity representation in LEAF – 2 guarantees an optimal physical description of surface latent heat and sensible heat flux, their respectively dominant regimes during wet or dry periods, and transition among them.

3. Heating rates satellite estimates

Surface soil water content can be measured using remote sensing instruments operating at low microwave frequencies (typically less than 10 GHz). Forthcoming satellite-borne instruments – such as the Advanced Microwave Scanning Radiometer (AMSR-E) and the Soil Moisture and Ocean Salinity Sensor (SMOS) - are about to provide surface soil moisture measurements at global scale. However, the low-frequency spectral band of the sensors and the polar-orbiting configuration of the satellites will not give rise to neither spatial nor temporal high-resolution measurements.

A possible alternative that complements a direct measurement of soil moisture is the assimilation of heating rates from a geostationary satellite in a land surface model. Satellite data can be used to infer the partitioning between latent and sensible heat fluxes, taking into account the influence of vegetation on the surface energy budget (McNider et al.1994).

Heating rates are derived from the Meteosat 8 SEVIRI thermal infrared channels (10.8 and 12 micron), which provide an estimate of the surface skin temperature at 3 km (at Nadir) spatial and 15 min. temporal resolution. Raw data over land are resampled at the model resolution and the satellite heating rate estimate for each model grid-box is calculated by estimating the satellite-derived surface temperature temporal gradient over three consecutive SEVIRI acquisitions.

Assimilation is performed during the mid-morning, period in which change in surface temperature is more sensitive to soil moisture than to other components in the surface energy budget.

It is important to note that such technique is especially suited for geostationary satellite acquisitions, since morning periods of maximum solar heating rate are not well covered by polar satellites passages. Furthermore, heating rates derived from different radiometers would suffer from inter-calibration discrepancies, which can be non-negligible in this kind of application and spoil the benefits of assimilation. Finally, the SEVIRI high measurement repetition rate and spatial resolution helps us minimize the number of pixels affected by clouds.

The assimilation approach presently implemented, described in the following paragraph, has the advantage of being conceptually very simple and constitutes a first step for assessing the potential benefits of assimilation of soil moisture for improving medium-range NWP forecasts. Future work will involve the development of a more sophisticated assimilation scheme with a proper treatment of observation and forecast errors. A possible candidate is the Ensemble Kalman Filter methodology, which does not require coding the adjoint of the model: the moderate number of variables in a land surface model makes the technique feasible despite its high computational cost (Crow and Wood, 2003).

4. RAMS soil moisture assimilation scheme

The method is in principle the same as the method implemented by Jones et al. 1998a and Jones et al. 1998b in which soil moisture in RAMS is adjusted upward or downward until the RAMS-simulated surface heating rate is in close agreement with the satellite-observed surface heating rate in each grid cell. However, there are many differences in how the scheme is implemented. Jones et al. 1998a, inverted many of the prognostic equations in the RAMS land surface model in order to derive a direct expression for the change of soil moisture that would lead to the desired change in modelled surface heating rate (to match observed values). A complete nonlinear analytic inversion was not possible, so a few iterations (usually 3 to 5) were required to achieve convergence.

The present method is much simpler to implement because it requires no inversion of the model equations. It simply carries out a forward integration of all or part of the model for a special assimilation period, usually about 1 hour, compares the model and observed surface heating rates, adjusts soil moisture upward or downward based on this comparison, and repeats the process. Each successive iteration, the moisture adjustment is smaller, and if 7 iterations are carried out, soil moisture will always be adjusted to within 1% of the "correct" assimilation value. This approach is very flexible and has many advantages over the approach taken by Jones et al. For one thing, one can very easily vary which processes are active or inactive in the model during the assimilation cycle. For example, one can include full atmospheric processes in the cycle, including precipitation, or one can hold atmospheric variables constant and only predict land surface and soil properties. Also, one can vary the relative adjustment of soil moisture as a function of depth in the soil, for example in case one wants only to modify shallow but not deep moisture in the assimilation process. A new derivation would be required of the equation set for each of these modifications if the inverted equations were to be used. Moreover, if the complete atmospheric model is included in the assimilation cycle, inversion of all equations is very complicated (this constitutes a full adjoint of the model, which is under development in other work). Probably the only disadvantage of the present method is the requirement of more iterations to achieve convergence, but even with twice as many iterations required, the entire assimilation process with only the land surface model active (as done in Jones et al.) adds less than 10% to the total computation time of most forecasts, and less than 5% in many cases.

A more important reason for using the present method is that the present land surface model in RAMS, which is called LEAF2, is very different from the earlier version used in the study of Jones 1998a. One of its special features is representation of multiple landuse types in a single surface grid cell by dividing the cell into subgrid patches. Energy and water of soil, vegetation, temporary surface water, and canopy air are prognosed separately in each patch, and surface fluxes are evaluated between each patch and the overlying atmospheric column. This greatly complicates the system of inverted equations and makes even more difficult any change in assumptions.

The present soil moisture adjustment process is carried out in the following way: the RAMS simulation is begun in a normal way, beginning from initial conditions and integrating forward in time for a few hours. At a specified time in the simulation which we denote here as TA1, usually chosen to be approximately 9 or 10 A.M. local time when surface warming from solar radiation is rapid, the model forward integration is temporarily halted and the assimilation process is carried out. The assimilation process involves a series of forward integrations of the surface model (LEAF2 only, with atmospheric conditions held constant in time) for a period of 1 hour, from TA1 to TA2. In the first iteration of the assimilation cycle, the forward integration of the surface model is initialized using current soil moisture values, WGP from the RAMS forecast. Then, for each grid cell, the average modelled surface heating rate over the period from TA1 to TA2 is compared against the observed value. Next, LEAF2 is reinitialized at TA1 for the second iteration. If on the previous iteration the model heated up more quickly than observation, soil moisture at TA1 is set to a value half way between WGP and WMAX, where WMAX is the maximum possible soil moisture content. If the model heated up more slowly than observation, soil moisture at TA1 is set to a value half way between WGP and WMIN, where WMIN is the minimum possible soil moisture content. The second forward integration to TA2 is carried out with LEAF2, and model heating rates are again compared with observation. To begin the third forward integration of LEAF2 from TA1 to TA2, soil moisture is adjusted upward or downward from the initial value on the previous iteration by 25% of the range (WMAX - WGP) or of the range (WGP - WMIN) based on this comparison. For the fourth iteration, the moisture adjustment is an increase or decrease of 12.5%, continuing with half the adjustment magnitude each iteration. Following the eighth iteration, the final moisture adjustment is about 0.4%, and the LEAF2 soil moisture values, WGP, are set to the assimilated values. Then, the model simulation proceeds forward from TA1 using the adjusted soil moisture.

In the assimilation code a weighting factor (WF), with values ranging from 0 to 1, is defined as a function of depth in the soil and is used to control the relative amount of soil moisture adjustment performed at each level in the soil, in case it is desired to not adjust uniformly at all levels. The soil moisture adjustment process is carried out as described above for any soil level k that has the WF = 1, and no adjustment is done for levels where WF = 0. Because shallow moisture in the soil usually impacts surface fluxes more than does deeper moisture, and because it may be desirable to minimize the total impact of the soil moisture adjustment process on the total water content of the soil, it has been defined a WF profile that is 1 at the surface, decreases linearly to 0 at a depth of 2/3 meter, and remains at 0 below that. It would be worthwhile to experiment with this weight profile in an operational setting.

Other parameters that control this assimilation procedure have been added to the RAMSIN namelist file in order to provide easy user-modification. They are the following:

- ***IOSHRFN*** - The filename of observed surface heating rate values. This namelist parameter is used in a manner identical with ITOPTFN, which is described in detail in the RAMS User's Guide.
- ***IOSTFN*** - The filename of observed surface temperatures. This namelist parameter is used in a manner identical with ITOPTFN, which is described in detail in the RAMS User's Guide.
- ***IOSHRFLG*** - The main flag that specifies whether or not to carry out this

assimilation process. If set to 0, no assimilation is done. If set to 1, the assimilation is carried out using the downward longwave and shortwave radiative fluxes that are current at the time (TA1) at which the assimilation cycle begins. If set to 2, RAMS will carry out the assimilation using downward radiative fluxes computed by (1) executing the RAMS Mahrer-Pielke radiative scheme, which assumes clear air, and (2) attenuating the downward shortwave fluxes in regions where clouds are deduced to be located. This deduction process consists of (1) reading in observed (satellite-based) radiative temperatures from the file named above in namelist variable IOSTFN, (2) comparing these values against RAMS predicted surface temperatures, (3) assuming that clouds exist whenever observed radiative temperatures are more than 10 K below the RAMS surface temperatures, and (4) reducing downward surface shortwave flux to 30% of its clear-air value. (This 30% factor is rather arbitrary and is another parameter that should be experimented with in an operational setting.)

- ***OSHRSTR*** - The specified starting time (TA1) at which the assimilation process will begin. This should correspond approximately to the time at which the observed surface heating rates were observed. OSHRSTR is defined as a number of seconds after the start of the model simulation (i.e., it corresponds to the RAMS 'time' variable.
- ***OSHRDUR*** - The period (TA1 to TA2) over which each forward integration of the surface model is carried out. It should normally be approximately 1 hour. OSHRDUR is defined in units of seconds.

5. DISCUSSION AND CONCLUSIONS

In this work we have described a methodology for a new RAMS data assimilation feature. It is part of a continuous effort towards a better description of soil state in NWP.

Besides being very simple to implement, this method also allows considerable flexibility. For example, it is possible to modify soil moisture at all levels, or instead limit the adjustment to the shallower layers, knowing that the latter are the most influential in determining surface heating rate. It is possible to hold the atmospheric conditions constant and only integrate the soil model during the assimilation cycle, or let the atmosphere respond to the changed soil moisture and feed back to the surface temperature during the assimilation cycle. Each of these choices can be implemented with a few IF statements in the code without any need for re-inverting the equation set each time and is thus a very attractive approach. Obviously, carrying out the assimilation cycle - 8 iterations over 1 hour - takes as long as running an 8-hour forecast if all model equations are included, but runs many times faster than this if only the soil model equations are solved so the additional time required is moderate, so it is possible a simple usage within an operational chain or long runs too.

Furthermore the method can be expanded to many other aspects of initialization of critical initial fields such as atmospheric liquid and ice content.

This strategy is under a deep testing phase, preliminary results seem promising thus encouraging not only an operational usage, but also for seasonal studies.

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